SuNAM's Coated Conductor Development for NMR/MRI Applications

Jae-Hun Lee, Ho-Kyum Kim, Jaemin Kim, Hunju Lee* and Seung-Hyun Moon

SuNAM Co., Ltd.

Contents

- What SuNAM is doing

- SuNAM’s coated conductor
  - CC architecture & process
  - RCE-DR process for superconducting layer
  - Quality control → Uniform, high-$I_C$ tapes

- New RCE-DR system
  - Introduction of pinning center; mid-T, mid-B $I_C$ enhancement
  - Preliminary results on various RE’s other than Gd

- Summary
What SuNAM is doing

2G HTS Tapes

High Field Magnets

18 T Research Magnet

400 MHz NMR Magnet
Electro polishing
IBAD (Buffer layers)
RCE-DR (Superconducting layer)
Ag coating
CCs

Protecting layer (~1 um)
Superconducting layer (~1.4 um)
Buffer layer (~40 nm)
Homo epi-MgO layer (~20 nm)
iBAD-MgO layer (~10 nm)
Seed layer (~7 nm)
Diffusion barrier (~40 nm)
Substrate (~100 um)

HTS 2G Wire Process of SuNAM

Hastelloy or Stainless steel
Al₂O₃
Y₂O₃
IBAD-MgO
Epi-MgO
La(Sr)MnO₃
RE₆Ba₂Cu₃O₇-δ
Ag

Invited presentation NM-5 was given at the virtual CCA 2021, October 11-15, 2021.
# Product Portfolio

## [2G HTS wire portfolio]

<table>
<thead>
<tr>
<th>Item</th>
<th>AN</th>
<th>CN</th>
<th>LBS / LSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cover layer</td>
<td>Silver</td>
<td>Copper</td>
<td>Brass / Stainless steel</td>
</tr>
<tr>
<td>Substrate</td>
<td>Non-Magnetic Stainless steel (STS310S ~104 um) or Ni-alloy (Hastelloy C-276 ~ 62 um)</td>
<td>Non-Magnetic Stainless steel (STS310S ~104 um) or Ni-alloy (Hastelloy C-276 ~ 62 um)</td>
<td>Brass / Stainless steel</td>
</tr>
<tr>
<td>Width [mm]</td>
<td>4 / 12 standard width</td>
<td>2/3/5/6/7/8/9/10 special order</td>
<td></td>
</tr>
<tr>
<td>Thickness [mm]</td>
<td>HAS : 0.10</td>
<td>HAS : 0.10</td>
<td>STG substrate only</td>
</tr>
<tr>
<td>*depending on Substrate</td>
<td>STS : 0.14</td>
<td>STS : 0.14</td>
<td>LBS : 0.29 / LSS : 0.23</td>
</tr>
<tr>
<td>Final Process</td>
<td>Sputter</td>
<td>Electro-plating</td>
<td>Single side Lamination</td>
</tr>
<tr>
<td>Critical Current (@ 77K s.f.)</td>
<td>4 mm width : &gt; 150 A, 200 A, 250 A</td>
<td>12 mm width : &gt; 500 A, 600 A, 700 A, 800 A</td>
<td></td>
</tr>
</tbody>
</table>

* Not to scale

**AN model**
- Single side Lamination
- Surrounded Copper layer
- Silver Cover layer
- Superconducting layer
- $Al_2O_3 / Y_2O_3 / MgO / LMO$
- Substrate
  - Non-magnetic Stainless steel or Hastelloy C-276

**CN model**
- Surrounded Copper layer

**LBS / LSS model**
- Surrounded Copper layer
RCE-DR for Superconducting Layer Deposition

- RCE-DR: Reactive Co-Evaporation by Deposition & Reaction (SuNAM, Reel-to-Reel)
- High rate co-evaporation at low temperature & pressure to the target thickness (> 1 μm) at once in deposition zone (6 ~ 10nm/s)
- Fast conversion (up to 100 nm/sec) from amorphous glassy phase to superconducting phase at high temperature and oxygen pressure in reaction zone
- Simple, high deposition rate, large deposition area...
- Easy to scale up: single path
- Verified for Gd, Y, Sm, Pr…

High production throughput, high $J_C$ & low cost
Quality Control: RHEED Vision System

- An appropriate feedback algorithm can keep the shape of the RHEED spot in the specific range, while QCM monitoring to adjust the e-gun power.
Feedback based on RHEED spot analysis

- Because of different evolution of $\Delta \phi$ & $\Delta \omega$, optimization is very important for high quality 2G wire.
- Intensity & tilt angle of MgO (110) spot is one of the most important parameter.
Quality Control: RCE Vision Inspection System

Based on color dependence of composition DB, optimum composition level is automatically controlled by PC. (Slow feedback)
Quality Control : RCE Vision Inspection System

- RCE Vision System will be introduced for increasing the uniformity of composition in RCE-DR process. The control computer takes (RGB) values in three-dimensional vector space which is transformed from the color of the tape surface.
Integration of process notes & wire performance

Hall measurement

IBAD RHEED spot

RCE color, pressure

In-line control and post analysis
Results of process optimization of in-line control
New RCE-DR system with 100 kW e-gun

- Installation of 100kW class e-gun on RCE-DR at the end of 2019.
- As e-gun power increases,
  - various pinning materials can be deposited (Zr, Hf, Sn etc.)
  - Deposition rate can be increased (10 nm/sec → > 25 nm/sec)
  - Other rare earth materials can be deposited (Y, Y-Gd, Sm etc.)
- Y : High power e-gun is required to sweep wide areas for stable long-length process
- Development of 40 mm ~ 120 mm-width coated conductor manufacturing process

Capacity increase, pinning center introduction and wider tape process
RCE-DR system with 100kW class e-gun

Various beam patterns can be applied to each material.

Remote Control and Monitoring Systems

Real-time Automatic Composition Control Program

100 kW class E-gun

Invited presentation NM-5 was given at the virtual CCA 2021, October 11-15, 2021.
Enhancement of in-field properties (ZrO$_2$ co-evaporation)

- Crystallinity by x-ray diffraction.
  - High quality YBCO even adding ZrO$_2$.
  - BZO randomly oriented growth.

**Resistance ($\mu\Omega$-cm) vs. Temperature (K)**

- $T_c = 88.8$ K
- $R(300$ K$/R(100$ K$) = 2.9$

**Intensity (arb. unit)**

- ZrO$_2$ added YBCO
  - YBCO (005) FWHM=2.35°
  - YBCO (103) FWHM=4.01°

**Substrate**

- YBCO(007)
- YBCO(006)
- YBCO(005)
- YBCO(003)

**YBCO (001)**
**YBCO (002)**
**YBCO (004)**
**MgO (002)**

**ZrO$_2$ added YBCO After oxygenation**

- BZO (110)
- CuO (002)
- Y$_2$O$_3$ (400)
- Y$_2$O$_3$ (222)
- YBCO (005)

**Intensity (arb. unit) vs. 2θ (degree)**

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Enhancement of magnetic properties by RCE-DR process

- TEM result: YBCO-ZrO$_2$
  - Second phases are observed as self-pinning center such as Y$_2$O$_3$, CuO$_x$ and Y$_2$Cu$_2$O$_5$
  - Y$_2$O$_3$ particles are close to spherical, not agglomerated in YBCO
  - While there are large Y$_2$Cu$_2$O$_5$ particles in top region, few Y$_2$Cu$_2$O$_5$ particles in bottom region: optimization in progress.

- BZO nanoparticles in YBCO
  - Visible in higher magnification image
  - About 10~20 nm in diameter
  - Random, non-uniform distribution: optimization in progress.
Home-made $I_C(B, T, \theta)$ measurement set-up

- Magnet manufactured circa 2013
- Conduction-cooling, no-insulation magnet
- Brass laminated tape was used
- Field up to 4 T
- Temperature down to 15 K
- Current up to 1,000 A
- Rotating sample holder

<table>
<thead>
<tr>
<th></th>
<th>100 mm</th>
<th>200 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of DPC</td>
<td>22</td>
<td>28+2(12 mm)</td>
</tr>
<tr>
<td>Number of turns</td>
<td>110</td>
<td>133</td>
</tr>
<tr>
<td>Tape length per DPC</td>
<td>111 m</td>
<td>232 + 255 m</td>
</tr>
<tr>
<td>Total tape length</td>
<td>2,452 m</td>
<td>6,496 + 510 m</td>
</tr>
</tbody>
</table>

- Magnet manufactured circa 2013
- Conduction-cooling, no-insulation magnet
- Brass laminated tape was used
- Field up to 4 T
- Temperature down to 15 K
- Current up to 1,000 A
- Rotating sample holder

203 mm RT 4T magnet

Insert cryostat

< $I_C(B-T-\theta)$ measurement system >
Enhancement of magnetic properties by RCE-DR process

- Production and optimization of new RCE-DR with 100kW e-gun installed to improve magnetic field characteristics.
- For YBCO-ZrO₂, the critical current under magnetic field increased more than twice compared to GdBCO, although 77 K, s.f. values are less than half those of GdBCO.
- Research is underway to add not only ZrO₂ but also various RE (rare earth) materials and pinning materials (Hf, Zr, etc.).
**Ongoing project plan in SuNAM**

### High Throughput: 2021~2025
- Increase production speed
- Wide-width CC (>100mm)

### Improve Yield: 2020~2021
- Development of automated quality control system

### High Performance: 2020~2022
- Improvement of magnetic properties
- Improve critical current in self field: >400A/4 mm

### Apply new process: 2021~2022
- Development of PLD process
- New sputtering system

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**Improvement for RCE-RGB feedback control with Machine Learning**

- **Center**: 428 A / 4 mm
- **Left**: 407 A / 4 mm
- **Right**: 435 A / 4 mm

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**Development of wide tape electro-polishing process is complete**

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**Development of wide tape electro-polishing process is complete**

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**Y, Yb, Eu, Dy, Nd**

**Zr, Hf**

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**Y-Yb, Zr etc.**
Summary

- SuNAM has been producing high $I_C$ coated conductors consistently.

- We set up a new machine to evaporate pinning materials.

- We found that incorporation of BZO is possible with RCE-DR process and achieved ~2.5X enhancement at 3 Tesla, 20 K.

- Optimization for higher field property is under way.
Thanks for Attention!