High field superconducting characteristics at low temperature of SmBa$_2$Cu$_3$O$_x$ coated conductor with artificial pinning center

Yutaka Yoshida
Nagoya university
Japan
Co-researchers

Y. Tsuchiya, Y. Ichino, S. Miura
(Nagoya university)
S. Awaji (Tohoku university)
K. Matsumoto (Kyushu institute of tech.)
T. Izumi
(National Institute of Advanced Industrial Science and Technology)
A. Ichinose
(Central Research Institute of Electric Power Industry)

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### Lattice constant of various APC materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Lattice constant [Å]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaTiO$_3$</td>
<td>3.989</td>
</tr>
<tr>
<td>BaSnO$_3$</td>
<td>4.117</td>
</tr>
<tr>
<td>BaHfO$_3$</td>
<td>4.171</td>
</tr>
<tr>
<td>BaZrO$_3$</td>
<td>4.192</td>
</tr>
<tr>
<td>Ba$_2$SmNbO$_6$</td>
<td>4.244**</td>
</tr>
<tr>
<td>BaCeO$_3$</td>
<td>4.397</td>
</tr>
</tbody>
</table>

### Notes

- $3.85\sim 3.90^*$
- SmBa$_2$Cu$_3$O$_y$
- BaZrO$_3$
- BaCeO$_3$
- BaSnO$_3$
- BaHfO$_3$

### Nanorod Particles

- SmBa$_2$Cu$_3$O$_y$
- BaTiO$_3$
- BaZrO$_3$
- Ba$_2$SmNbO$_6$
- BaCeO$_3$

### References

12. Y. Ichino JJAP 56 73101(2017)

* 11.72 Å/3 ~ 3.90 Å (RT)

- **Nanorod**
  - Misfit: 6.4%
  - Size: ~ 15 nm
- **YBCO + BaYNbO$_6$**
  - Misfit: 9.7%
  - Size: ~ 3-12 nm
- **(Y,Gd)BCO + Ba(Y,Gd)TaO$_6$**
  - Misfit: ~ 15 nm
  - Size: ~ 7 nm
  - Misfit: ~ 9.5%

Table of the Contents

✓ Motivation
Early studies of the film on single crystalline substrate

✓ Experimental
Reel to reel system by PLD
novel PLD technique

✓ Highlight data
Coated conductor on IBAD tape

✓ Summary
**Experimental facility**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser source</td>
<td>KrF eximer laser ($\lambda = 248$ nm)</td>
</tr>
<tr>
<td>Substrate</td>
<td>LaAlO$_3$(100) IBAD tape</td>
</tr>
<tr>
<td>Substrate temperature</td>
<td>700~950 °C</td>
</tr>
<tr>
<td>Oxygen partial pressure</td>
<td>0.4 Torr</td>
</tr>
<tr>
<td>Laser fluence</td>
<td>2 J/cm$^2$</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10 Hz</td>
</tr>
</tbody>
</table>

KrF excimer laser

Chamber

Substrate temperature 700~950 °C

Oxygen partial pressure 0.4 Torr

Laser fluence 2 J/cm$^2$

Repetition rate 10 Hz

O$_2$ gas

Vacuum

LTG - low temperature growth technique

Nagoya University
With seed layer, we can fabricate purely c-axis oriented films at lower $T_s$. 

13th European Conference on Applied Superconductivity, EUCAS 2017
Plane-view images of the TEM

**LaAlO$_3$ single crystalline substrate**

<table>
<thead>
<tr>
<th></th>
<th>diameter [nm]</th>
<th>Density [μm$^{-2}$]</th>
<th>$B_\phi$ [T]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LTG-sample</strong></td>
<td>7.0</td>
<td>2800</td>
<td>5.8</td>
</tr>
<tr>
<td><strong>PLD-sample</strong></td>
<td>13.5</td>
<td>708</td>
<td>1.5</td>
</tr>
</tbody>
</table>


Microstructure in SmBCO+BMO film

Growth temperature

- Diameter: 4 nm
  - Number density: 3100 /µm²
  - Maximum tilt angle: ~35°
  - Discontinuity

- Diameter: 6 nm
  - Number density: 2300 /µm²
  - Maximum tilt angle: ~25°

- Diameter: 13.5 nm
  - Number density: 710 /µm²
  - Maximum tilt angle: ~5°

Distribution of inclination angles of the BHO nano-rods

High number density
Small diameter
tilt for c-axis

Straight
Low number density

Miura, Yoshida; APL mater. 4 (2016) 016102
A diagram of the growth process of BHO nanorods in growth–kinetics

High-\(T_s\) sample

Migration length of BHO and SmBCO is large, Nucleation grows up at BHO only. **Straight**

Low-\(T_s\) sample

Migration length of BHO and SmBCO is small, and the crystal nucleation frequency of BMO increases, and high density BMO nanorods grow. So growth rate of BMO is low in the \(c\)-axis direction. Nucleation grows up in every step and terrace **tilt for \(c\)-axis**
$F_p - B$ at 77 K and lower temperatures

**$F_p - B$ at 77 K**

PLD (SmBCO + BHO) @ 77 K, $B//c$

High $F_p$ @ 77 K [3]

LTG

Fig. Magnetic field dependence of $F_p$ of the LTG and PLD high $F_p$ films.

Table Maximum $F_p$ of the LTG and PLD high $F_p$ films.

<table>
<thead>
<tr>
<th>Film</th>
<th>$F_p^{\text{MAX}}$ at 77 K</th>
<th>$F_p^{\text{MAX}}$ at 40 K</th>
<th>$F_p^{\text{MAX}}$ at 20 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTG 5.6vol%</td>
<td>14.2 GN/m$^3$</td>
<td>407 GN/m$^3$</td>
<td>779 GN/m$^3$</td>
</tr>
<tr>
<td>PLD high $F_p$</td>
<td>sample</td>
<td>28.0 GN/m$^3$</td>
<td>226 GN/m$^3$</td>
</tr>
</tbody>
</table>

$J_c$–B & $F_p$ of the LTG–SmBCO+BHO films @4.2K

Maximal $F_p$ reached $1.6 \, \text{TN/m}^3$.

$F_p$ of $1.6 \, \text{TN/m}^3$ was realized; this value was comparable to the highest value recorded at 4.2 K and under 17 T.

$T_s^{\text{upper}} = 720^\circ \text{C}$

$B_{//c}$

$J_c (\text{MA/cm}^2)$

$F_p (\text{TN/m}^3)$

@ 4.2 K, $B_{//c}$

15% Zr-added MOCVD

A. Xu et al.: APL Mater. 2 (2014) 046111

S. Miura, Y. Yoshida et. al.; APL mater. 4 (2016) 016102
Main Topics

Improvement of the superconducting properties and controlling microstructures of the REBCO coated conductor with BMO nanorods on IBAD tape

- Improvement of $F_p$ at 4.2K and 20K of SmBCO+BHO on IBAD tape fabricated LTG
- Growth mechanism and sharp of the BMO nanorods fabricated with the high-speed growth technique
SmBCO+BHO / IBAD tape fabricated by RTR system

**Parameter** | **Condition**
--- | ---
Deposition method | ALT-PLD + LTG
Substrate | IBAD-MgO
Targets | SmBa2Cu3Oy
O2 pressure | 0.4 Torr
Laser frequency | 10 Hz
Energy density | 1.7 J/cm²
Laser source | KrF excimer laser (λ = 248 nm)
BHO content | 3.8vol.%
Thickness | 240-440 nm
The number of laser pulses in each cycle (SmBCO : BHO) | 30 : 5

**Growth temp.: 840 °C**
Seed growth temp.: 840 °C
Upper growth temp.: 750 °C

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**LTG film**
Seed growth temp.: 840 °C
Upper growth temp.: 750 °C

**HTG film**
Growth temp.: 840 °C

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**Nano-rods**
~30 nm
~400 nm

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**CeO2 (600nm)**
**Gd2Zr2O7 (55nm)**
**MgO (5nm)**
**Y2O3 (14nm)**
**Hastelloy (100µm)**
**LaMnO3 (8nm)**

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**O2 gas**
**Vacuum**

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**KrF excimer laser**

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**Chamber**
**Heater**
**Substrate**
**Plume**

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**O2 gas**

---

**Vacuum pump**
**BHO nano-rods morphology**

**LTG versus HTG film on IBAD**

**LTG film**

- High number density
- Small diameter
- Tilt for c-axis

**HTG film**

- Straight
- Low number density

Discontinuous
Small diameter ~ 4 nm
Fireworks structure

SmBCO + BHO
SmBCO seed layer
CeO$_2$

100 nm

Straight and continuous
Diameter ~ 5.4 nm

SmBCO + BHO
CeO$_2$

50 nm

HTG film fabricated at high $T_s$ by PLD (conventional PLD)

The TEM image on left figure was taken by Mr. Shun Ito at IMR, Tohoku Univ.
The TEM image on right figure was taken by Dr. Ataru Ichinose at CRIEPI.
Flux pinning force and field angle dependence of $J_c$ @ 4.2 and 77.3 K

- $F_p$ at 77K of LTG SmBCO+BHO is low. However, $F_p$ at 4.2K is 1.5 TN/m$^3$ at 4.2 K.
Main Topics

Improvement of the superconducting properties and controlling microstructures of the REBCO coated conductor with BMO nanorods on IBAD tape

- Improvement of $F_p$ at 4.2K and 20K of SmBCO+BHO on IBAD tape fabricated LTG

- Growth mechanism and sharp of the BMO nanorods fabricated with the high-speed growth technique

Simulation results

BHO Nano rod

high growth rate $\Rightarrow$ Miniaturization of nanorod

$\nu_{dep} = 70$ nm/h  
$\nu_{dep} = 300$ nm/h  
$\nu_{dep} = 3,000$ nm/h

The growth direction of the BHO nanorods by plotting a histogram of the inclination angles using High-speed growth technique.

Growth rate: 12 nm/min at 50 Hz

Growth rate: 25 nm/min at 100 Hz

Thickness of nanorod:
- 50 Hz: 4 ~ 6 nm
- 100 Hz: 3 ~ 5 nm

Density:
- 50 Hz: 2188 /μm³
- 100 Hz: 3281 /μm³

$B_\phi$:
- 50 Hz: 4.52 T
- 100 Hz: 6.78 T

Thinner diameter, higher number density, tilted
**F_p and Field angle dependence of J_c of the SmBCO+BHO on IBAD by High-speed growth technique**

We will describe the development of the coated conductor fabricated with a repetition rate of 100 Hz, changed from 10 Hz.

As increasing laser frequency, $J_{c\text{min}}$ of the SmBCO–coated conductor fabricated by high-speed growth was higher than the SmBCO–coated conductor by conventional speed growth.
Summary

For the high $J_c$ coated conductor, we have investigated the relationships among changing of $T_c$, $J_c$, and $B_{irr}$, growth temperature, the variety of BMO materials, its amount of additive, the kind of substrate, the surface morphologies et al.

- Using the low temperature growth technique with the seed layer, we can design and control the higher density and fine BHO nanorods grown in high quality SmBCO film, as changing lower substrate temperature.
- Higher $F_p$ at 10K and 4.2K at optimum $T_s$ and BMO volume. $F_p$ at 77K of LTG SmBCO+BHO is low. On the other hand, $F_p$ at 4.2K is 1.6TN m$^{-3}$ at 4.2 K.
- LTG SmBCO+BHO on IBAD–MgO tape has $F_p=260$ GN m$^{-3}$ at 40 K, 690GN m$^{-3}$ at 20 K, and 1.5 TN m$^{-3}$ at 4.2 K, respectively.

- The high-speed growth technique for high performance SmBCO coated conductor is an important subject. In this presentation, we described the development of the coated conductor fabricated with a repetition rate of 100 Hz, changed from 10 Hz. We discussed the details of microstructures and superconducting properties of BHO nanorods in SmBCO coated conductor using the laser system with high repetition rate.
Thank you for your attention
Field angle dependence of $J_c$ and the pinning phase diagram of the ratio of $J_c^{\text{rand}}$ to the total $J_c$ as a function of the magnetic field and temperature.

The range at 20-40K is advantage using LTG sample.

**Double type pin** (cooperated by Random/correlated pin)

Sm123+3.8vol.%BHO

B//c

Temperature (K)

Magnetic field (T)

Temperature, $T$ [K]

Calculated by Effective mass model

SmBCO + 3.8 vol.% BHO/metal sub.

$J_{c}^{\text{min}}$ of LTG / $J_{c}^{\text{min}}$ of HTG

Random pin

Correlated pin

Slightly correlated with c-axis 1D BMO nano-rod

Randomly distributed OD oxygen vacancy, precipitation

S. Miura SUST(2017) 30 (2017) 084009


13th European Conference on Applied Superconductivity, EUCAS 2017
TEM images of the HTG SmBCO

Table:

<table>
<thead>
<tr>
<th>$d_{BHO}$ [nm]</th>
<th>$n_{BHO}$ [$\times 10^3$ $\mu$m$^{-2}$]</th>
<th>$B_p$ [T]</th>
<th>FWHM [$^\circ$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.4 ± 0.9</td>
<td>2.8 ± 0.1</td>
<td>5.8 ± 0.3</td>
<td>1.1</td>
</tr>
</tbody>
</table>

straight-shaped BHO nanorods grow from the bottom to the surface.
The $J_c$ at the self-field are 8.4 MA/cm² and 3.5 MA/cm² at 65 K and 77.3 K.

The maximum $F_p$ values of 120 GN/m³ and 32.5 GN/m³ were obtained at 65 K and 77.3 K.