Vortex Dynamics in Superconductors at High Vortex Densities

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DEPARTMENT OF PHYSICS

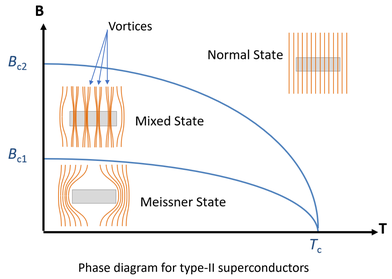
Introduction

Superconductors are materials which can support current with zero resistance below a characteristic critical temperature, T_c. The maximum current that a superconductor may carry while maintaining zero resistance is its critical current, J_c. To date, no type II superconductors have achieved a J_c greater than 25 - 30% of their theoretical maximum, J_d. Moreover, J_c decreases under the influence of magnetic fields due to dissipation caused by the motion of magnetic vortices. However, it is predicted that J_c may be greatly enhanced through the pinning of multiple magnetic vortices to nanoparticle inclusions in superconducting films. The goal of this project is to look for the theoretically predicted magnetic signature of nanoparticles capturing more than one vortex and to further understand vortex dynamics at high vortex densities. Here, we present our preliminary characterization of three $(Y_{0.77}, Gd_{0.23})Ba_2Cu_3O_y$ films: one contains no added inclusions, the second contains $BaSnO_3$, and the last contains $BaHfO_3$ nanoparticles. Measurements at low fields (up to 7 T) have been collected in preparation for high field measurements (up to 35 T) which will be taken at the National High Magnetic Field lab in May of 2019.

Background

Superconductors

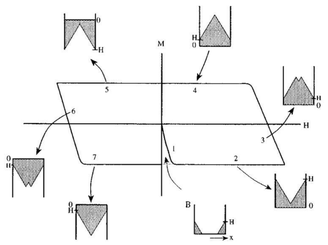
- Superconductors exhibit zero resistance once cooled below a characteristic critical temperature (T_c)
- Vortices (quantized bundles of magnetic flux) form in type-II superconductors when exposed to magnetic fields above B_{c1}



Phase diagram for type-II superconductors

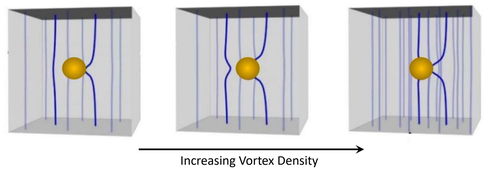
Bean Critical State Model

- Extract J_c from magnetization
- Changes in flux distribution begin at the surface of a sample
- Hysteresis loop: reversible magnetization



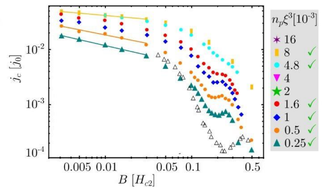
Hysteresis loop of magnetization (M) of a flat sample penetrated on opposite sides by applied field *H*. Profiles of flux penetration are shown at corresponding points in the cycle. [Figure from Ref. 3]

Multiple Vortex Pinning



- Vortex motion introduces dissipation which may be slowed by nanoparticles
- Individual vortex pinning increases the J_c of a sample

Theory We Aim to Prove

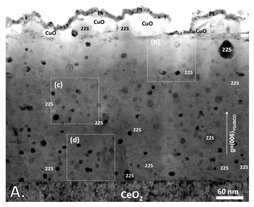


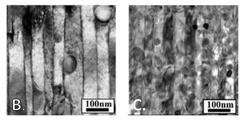
Simulations suggest that nanoparticles could pin multiple vortices, resulting in a nonmonotonic dependence of J_c on field. This simulation was based off of the time-dependent Ginzburg Landau theory. [Figure from Ref. 4]

Sample Information

	$(Y_{0.77}, Gd_{0.23})Ba_2Cu_3O_y$	$(Y_{0.77}, Gd_{0.23})Ba_2Cu_3O_y + BaSnO_3$	$(Y_{0.77}, Gd_{0.23})Ba_2Cu_3O_y + BaHfO_3$
Abbreviation	*BCO*	*BSO*	*BHO*
Nanoparticle Diameter	-	40 ± 5 nm	14 ± 5 nm
Nanoparticle Density	-	2×10^{21} np/m^3	65×10^{21} np/m^3
Sample Dimensions	3.0×2.9 mm	3.2×3.1 mm	3.0×3.0 mm
Thickness	900 nm	900 nm	900 nm

- Critical parameters for $(Y_{0.77}, Gd_{0.23})Ba_2Cu_3O_y$:
  $B_{c2}(\mathrm{T} = 0\ \mathrm{K}) \approx 120$ T , $T_c = 93$ K [7]
- All films were grown using metal organic deposition and contain a low density of $R_2Cu_2O_5$, $R = (\mathrm{Y}, \mathrm{Ba})$ precipitates
  - Diameter: 94 ± 5 nm
  - Density: $0.03 \times 10^{21}5$ np/m^3





TEM images of sample films. Twin boundaries (visible in B. and C.) are present in all YBCO films and increase with nanoparticle density. **A.** (Y,Gd)BCO + BHO **B.** (Y,Gd)BCO **C.** (Y,Gd)BCO + BSO [Figure from Ref. 5]

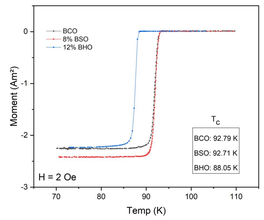
Experimental Method

- To characterize the field and temperature dependence of J_c , magnetization curves of each sample were collected from 2K to 65K under magnetic fields (H // c) up to 7 T
- Measurements were acquired using an MPMS XL magnetometer
- We used the Bean Model to extract J_c from magnetization:

$$J_c = \frac{20\Delta M}{W\left(1 - W/3L\right)}$$

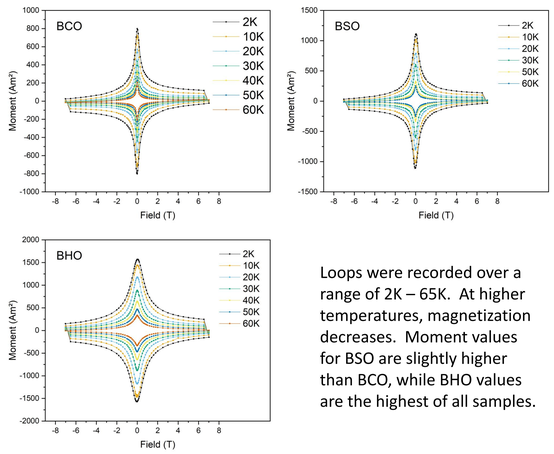
where $M \equiv$ Magnetization, $W \equiv$ sample width, $L \equiv$ sample length

Critical Temperature



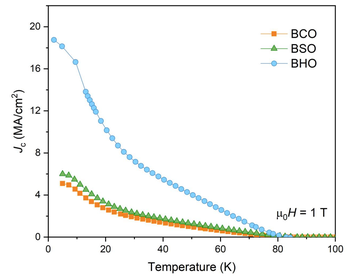
Temperature vs. moment curves for each sample. T_c of BHO is suppressed with respect to the BCO and BSO films.

Magnetic Hysteresis Loops

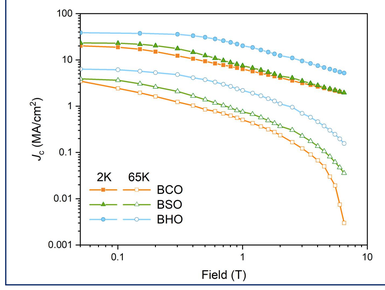


Loops were recorded over a range of 2K – 65K. At higher temperatures, magnetization decreases. Moment values for BSO are slightly higher than BCO, while BHO values are the highest of all samples.

Critical Current Comparisons

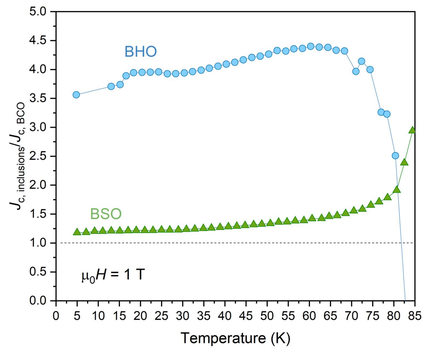


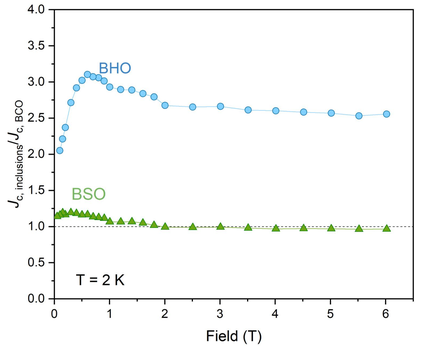
J_c was consistently highest for BHO at all T with a termination of superconducting state above T_c for all films.



Similarly, J_c was highest for BHO at all fields.

J_c Enhancement by Nanoparticle Inclusions





Comparison of J_c values as a normalization of BHO and BSO over BCO. Most results show an enhancement of J_c in films including nanoparticles, except for at higher fields.

Conclusions

- Characterization of films was accomplished in preparation for NHMFL
- The BHO film displayed a higher J_c than BSO, suggesting that a higher density is more effective at low fields for increasing J_c than a greater nanoparticle size

Future work

- High field tests will be performed at the NHMFL; nonmonotonic behavior of J_c is theorized due to multiple vortex pinning
- Correlations between nanoparticle density, size vs. coherence length, and non-monotonicity in current capacity will be characterized for samples with different nanoparticle inclusions

Acknowledgements

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