Visualisation of magnetic flux in high-quality YBCO films synthesized by cost-effective environmental-friendly techniques

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Introduction

- Films of the high-temperature superconductor $YBa_2Cu_3O_x$ (YBCO) synthesized by chemical solution deposition (CSD), such as by metal-organic deposition (MOD), often uses the toxic material trifluoroacetate (TFA).

- We have synthesized films by fluorine-free and low-fluorine MOD.

- Magneto-optical imaging has been used for obtaining live images of magnetic flux penetrating into the samples, and analysing local information from superconducting films, clarifying how micro and nano defects influence critical current density $\boldsymbol{j_c}$.

Overview of specimens

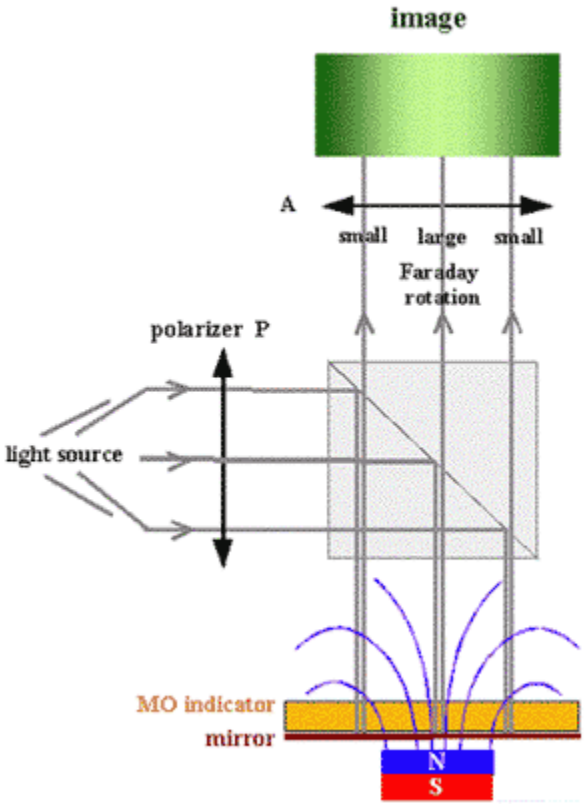
The films were synthesized by spin-coating and subsequent heat treatment.

Overview of the films synthesized in the present work. (MOD = metal-organic deposition and TFA = trifluoroacetate.)

Sample	Film thickness (nm)	Substrate	Synthesis method
Sample 1	220	Standard $LaAlO_3$	Low-fluorine MOD using TFA [1]
Sample 2	210	Standard $LaAlO_3$ with twins	Fluorine-free MOD using propionic acid [2]
Sample 3	305	10° miscut $LaAlO_3$	Low-fluorine MOD using TFA [1]

[1] Y. Zhao, W. Wu, X. Tang, N. H. Andersen, Z. Han and J.-C. Grivel, *CrystEngComm* **16** (2014) 4369.
[2] Y. Zhao, P. Torres, X. Tang, P. Norby and J.-C. Grivel, *Inorg. Chem.* **54** (2015) 10232.

Magneto-optical imaging



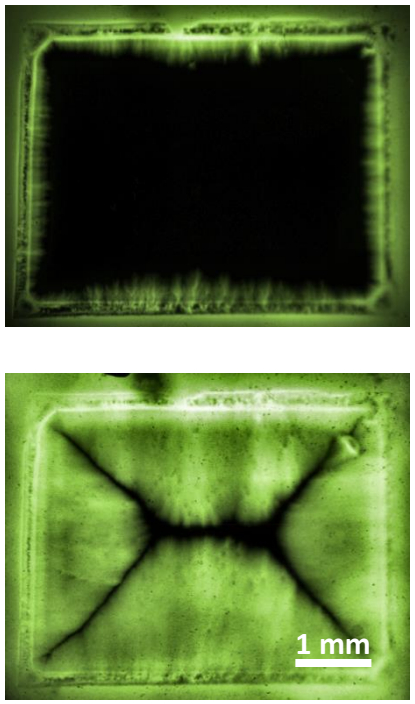
Magneto-optical imaging (MOI) is used for visualising magnetic flux in superconductors.

http://www.mn.uio.no/fysikk/english/research/groups/amks/superconductivity/mo/, downloaded on 15.05.2017

Sample 1 (low-fluorine MOD, standard substrate)

17 mT

78 mT



MOI images of sample 1 [1]. The film was zero-field cooled to 20 K and a magnetic field was subsequently applied perpendicular to the film.

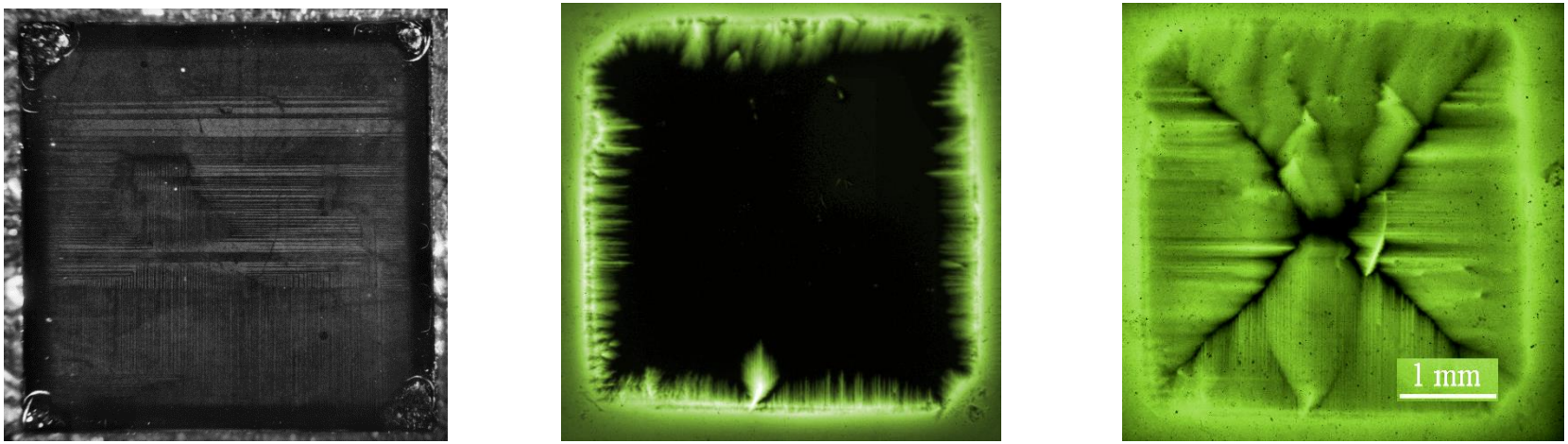
$$j_c = \frac{\pi H_a}{d} \Big/ \operatorname{acosh}\left(\frac{w}{w-L}\right)$$

H_a: applied magnetic field
d: film thickness
L: visible length of flux penetration from the edge
w: half of the sample's width

Using the equation above [2] and L from the lower edge at 17 mT, we find that $j_c = 2.1 \cdot 10^7$ A/cm^2.

[1] T. Qureishy, Y. Zhao, Y. Xu, J. I. Vestgården, T. H. Johansen, J.-C. Grivel, H. Suo and P. Mikheenko, Published online in *Adv. Mat. Lett.* (2016).
[2] E. H. Brandt and M. Indenbom, *Phys. Rev. B* **48** (1993) 12893.

Sample 2 (fluorine-free MOD, standard substrate with twins)

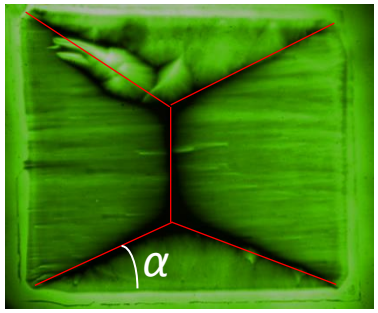


Optical (left) and MOI images (centre, right) of sample 2 [1]. The film was zero-field cooled to 20 K and a magnetic field was subsequently applied perpendicular to the film.

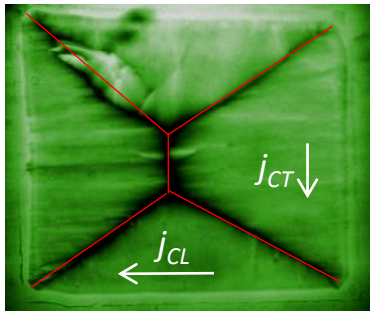
- Horizontal and vertical lines are caused by twin boundaries in the substrate and film, resulting in striped penetration of magnetic flux.
- By measuring L from the upper edge at 17 mT, we find that j_c = $2.4 \cdot 10^7$ A/cm^2.

[1] T. Qureishy, Y. Zhao, Y. Xu, J. I. Vestgården, T. H. Johansen, J.-C. Grivel, H. Suo and P. Mikheenko, Published online in *Adv. Mat. Lett.* (2016).

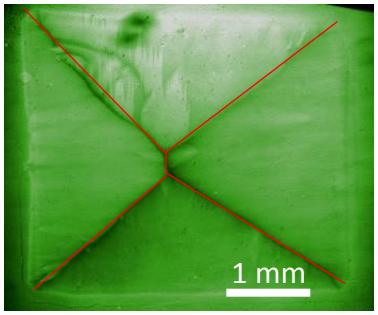
Sample 3 (low-fluorine MOD, 10° miscut substrate)



T = 6 K
$\mu_0 H$ = 68 mT
Γ = 2.0 and 2.4



T = 20 K
$\mu_0 H$ = 68 mT
Γ = 1.3 and 1.7



T = 72 K
$\mu_0 H$ = 34 mT
Γ = 1.2 and 1.6

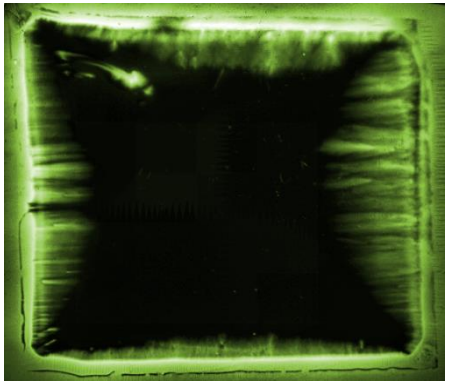
- Figures above: MOI images of sample 3 [1]. The film was zero-field cooled to different temperatures and a magnetic field was subsequently applied perpendicular to the film.

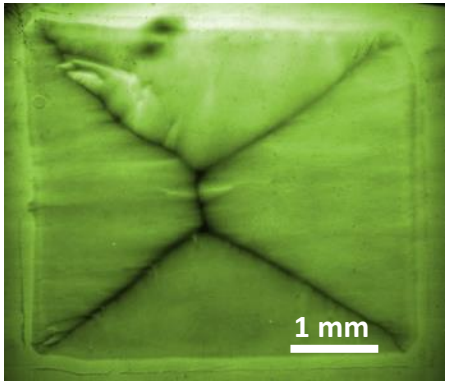
- Anisotropy ratio $\Gamma = \tan \alpha = j_{cL}/j_{cT}$ decreases with increasing temperature.

[1] T. Qureishy, Y. Zhao, Y. Xu, J. I. Vestgården, T. H. Johansen, J.-C. Grivel, H. Suo and P. Mikheenko, Published online in *Adv. Mat. Lett.* (2016).

Sample 3 (low-fluorine MOD, 10° miscut substrate)

17 mT





85 mT

MOI images of sample 3 [1]. The film was zero-field cooled to 20 K and a magnetic field was subsequently applied perpendicular to the film.

- By measuring *L* from the upper edge at 17 mT and using anisotropy ratios, we find that $j_{cL} = 1.8 \cdot 10^7$ A/cm^2, $j_{cT(left)} = 1.4 \cdot 10^7$ A/cm^2 and $j_{cT(right)} = 1.1 \cdot 10^7$ A/cm^2.
- Horizontal lines are seen in MOI images. The film contains planar defects, caused by the step-like structure of the substrate.
- Repeated nanoscale step-like surface developing in-plane anisotropy of j_c and striped (needle-like) flux penetration pattern in the direction of steps. The stripy structure helps to improve j_c in the film in the direction parallel to the stripes.

[1] T. Qureishy, Y. Zhao, Y. Xu, J. I. Vestgården, T. H. Johansen, J.-C. Grivel, H. Suo and P. Mikheenko, Published online in *Adv. Mat. Lett.* (2016).

Comparison with previous results

Critical current density j_c at 20 K in YBCO films synthesized by fluorine-free chemical solution deposition.

Reference	Year	Substrate	j_c (10^6 A/cm^2)
Bubendorfer et al. [1]	2003	$SrTiO_3$, $LaAlO_3$ and MgO	1-2
Cui et al. [2]	2009	$LaAlO_3$	2.5
Qureishy et al. [3]	2016	$LaAlO_3$ with twins	24

[1] A. J. Bubendorfer, T. Kemmitt, L. J. Campbell and N. J. Long, *IEEE Trans. Appl. Supercond.* **13** (2003) 2739.
[2] W. Cui, P. Mikheenko, L. M. Yu, T. W. Button, J. S. Abell and A. Crisan, *J. Supercond. Novel Magn.*, **22** (2009) 811.
[3] T. Qureishy, Y. Zhao, Y. Xu, J. I. Vestgården, T. H. Johansen, J.-C. Grivel, H. Suo and P. Mikheenko, Published online in *Adv. Mat. Lett.* (2016).

Conclusion

- We have synthesized high-quality YBCO films with a cost-effective, eco-friendly spin-coating technique.
- Three different films were investigated with MOI.
- j_c at T = 20 K in our film made from fluorine-free CSD is almost 10 times higher than what has been reported previously, and close to values obtained in films made by pulsed-laser deposition and high-fluorine TFA CSD.
- There were twin boundaries in the film grown on a substrate containing twins, resulting in striped penetration of magnetic flux.
- The film deposited on a miscut substrate contained planar defects, resulting in striped penetration of magnetic flux and global anisotropy of j_c.