Increased pinning strength in 2nd generation REBCO coated conductors grown by liquid assisted processes.

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1. Introduction

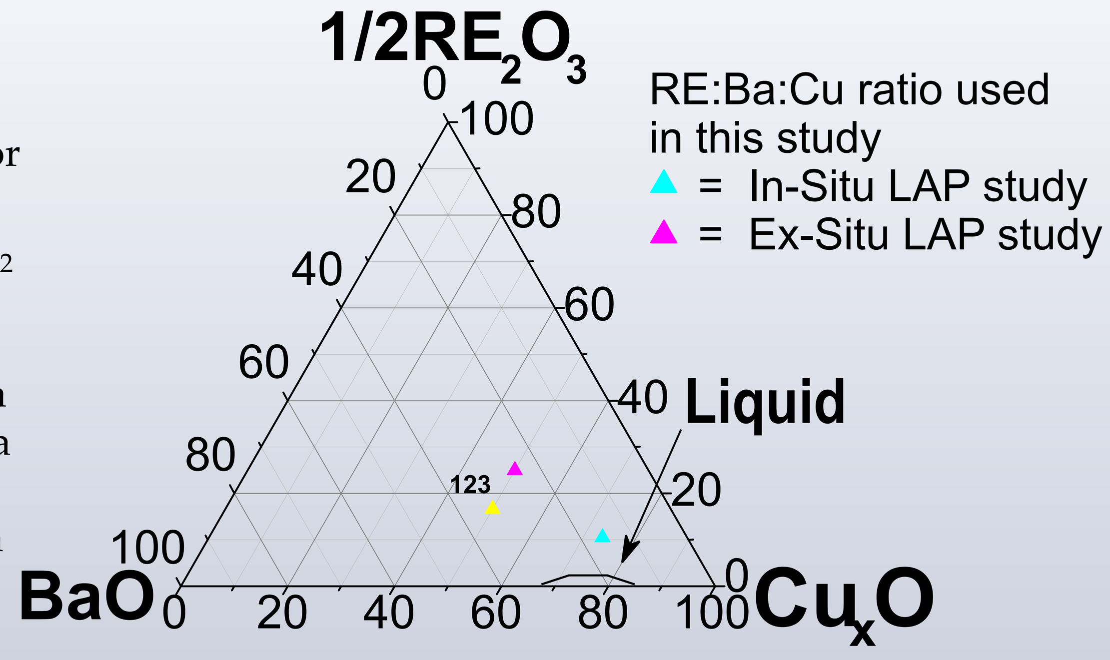
Second generation coated conductors

- Secondary generation $ReBa_2Cu_3O_{7-X}$ (REBCO) tape has the potential to substantially improve the efficiency of hundreds of products across a variety of sectors.
- To achieve this potential new methods are needed that can improve the cost of using the tapes and increase the pinning together.

Our work

- We are aiming to use liquid assisted processing (LAP) routes to grow films at an exceptionally a fast rate, thereby increasing production throughput and lowering costs.
- LAP is a PVD method where the film (here REBCO) grows from a liquid layer induced by control of the RE:Ba:Cu stoichiometry, *T*, pO2, etc as shown in Fig 1. The high rates of diffusion in liquids allow for very fast rates of REBCO formation [1].
- The liquid layer can either be present during deposition (in-situ LAP) or be induced after the deposition of an initial layer (ex-situ LAP).
- We have combined LAP with various techniques to create optimised pinning centre microstructures to generating films with both fast growth and strong performance.

Figure 1. Schematic Ternary phase diagram for the RE-Ba-Cu system at ~ 850 °C and 10^{-5} Torr pO_2 [2]. For a film to contain liquid under these conditions it must have a composition that lies on a tie line (not shown) between the liquid and a stable phase e.g. RE_2O_3.



2. In-situ Liquid Assisted Processing

- In-situ LAP requires a thin liquid layer to be present throughout the deposition. The depositing flux supersaturates the liquid on contact, inducing a film (here REBCO) to precipitate out (see Fig 2).
- The biggest problems facing this method are stopping the liquid layer reacting with the substrate and, as the fast diffusivity leads to highly perfect REBCO crystals [3], creating strong pinning centres.

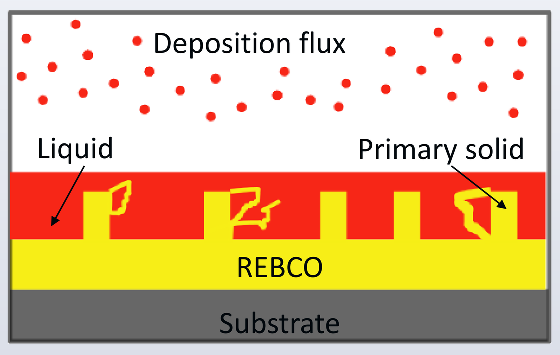


Figure 2. In-situ liquid assisted processing.

3. Ex-situ Liquid Assisted Processing

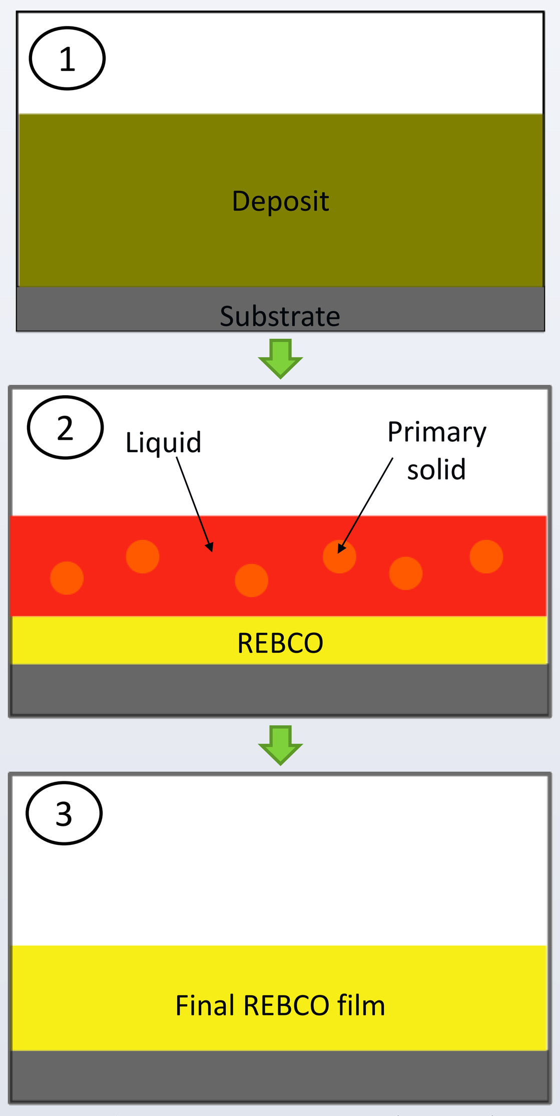


Figure 3. Ex-situ liquid assisted processing. Stages 1,2 and 3 are identified in the text.

- Ex-situ LAP is a three stage process (see Fig 3):
  (1) A pre-layer must be deposited.
  (2) The conditions must be changed so that this film melts.
  (3) The conditions must be changed again so that this liquid crystallizes as the desired REBCO layer.
- The best example of this method is the reactive co-evaporation by deposition and reaction (RCE-DR) used by SuNAM Co. LTD. [4]. Here an amorphous pre-layer is deposited by e-beam deposition. The film is then taken through specific *T* and pO_2 conditions (see Fig 4) to transform it into REBCO via an intermediate liquid phase.
- The main pinning centres in these REBCO films are 75-150 nm diameter Gd_2O_3 particles. For a stronger performance, especially in high-field-low-*T* conditions [5][6], a better microstructure would have more, smaller, Gd_2O_3 particles.
- One of the biggest challenges facing this method is generating smaller Gd_2O_3 particles without sacrificing the fast growth rates.

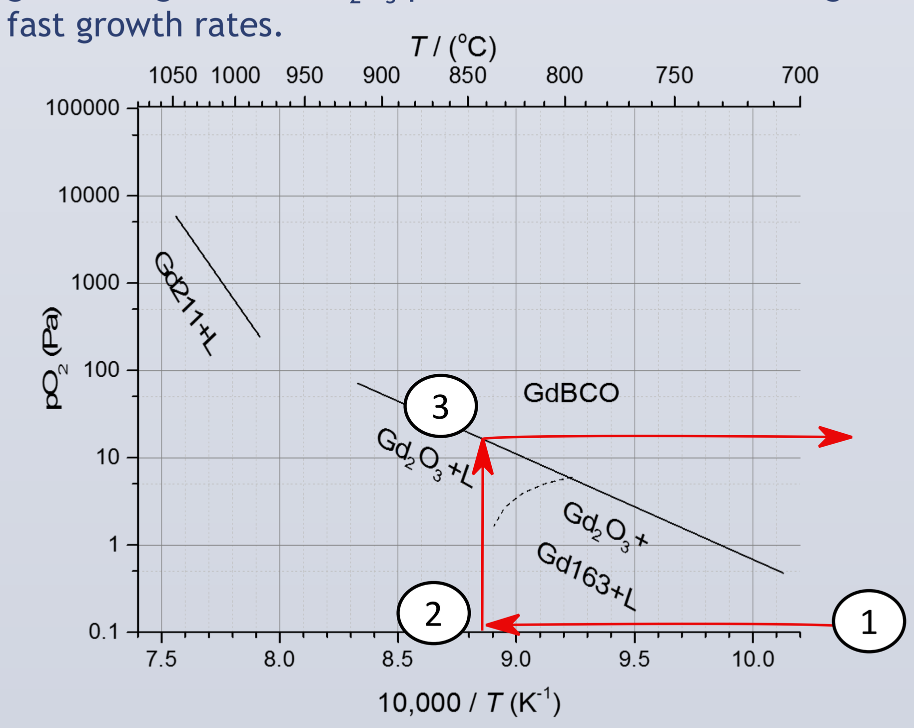


Figure 4. Stability diagram showing the RCE-DR process used by SuNAM Co. Ltd. An amorphous film (1) is processed by heating at low pO_2 (2) and then raising the oxygen pressure (3) to transform the film into GdBCO and trapped Gd_2O_3 particles via an intermediate liquid phase.

4. Results

In-situ

- We have grown YBCO films with a variety of APCs using pulsed laser deposition.
- Careful control of the Y:Ba:Cu stoichiometry meant a mushy zone (combined liquid and solid dendrites) not a full liquid layer formed at the deposition temperature, which limited the reaction between the liquid and the substrate.
- Strong pinning centres were formed by using dopants with low melting point oxides, so fast diffusion rates e.g. using Nb (m.p. Nb_2O_5 = 1512 °C) over Zr (m.p. ZrO_2 = 2715 °C). This allowed secondary phase columns to form despite the high YBCO growth rates.
- The films produced had superior performance to pure-YBCO and YBCO+BYNO films made using standard PLD (see Fig 5).

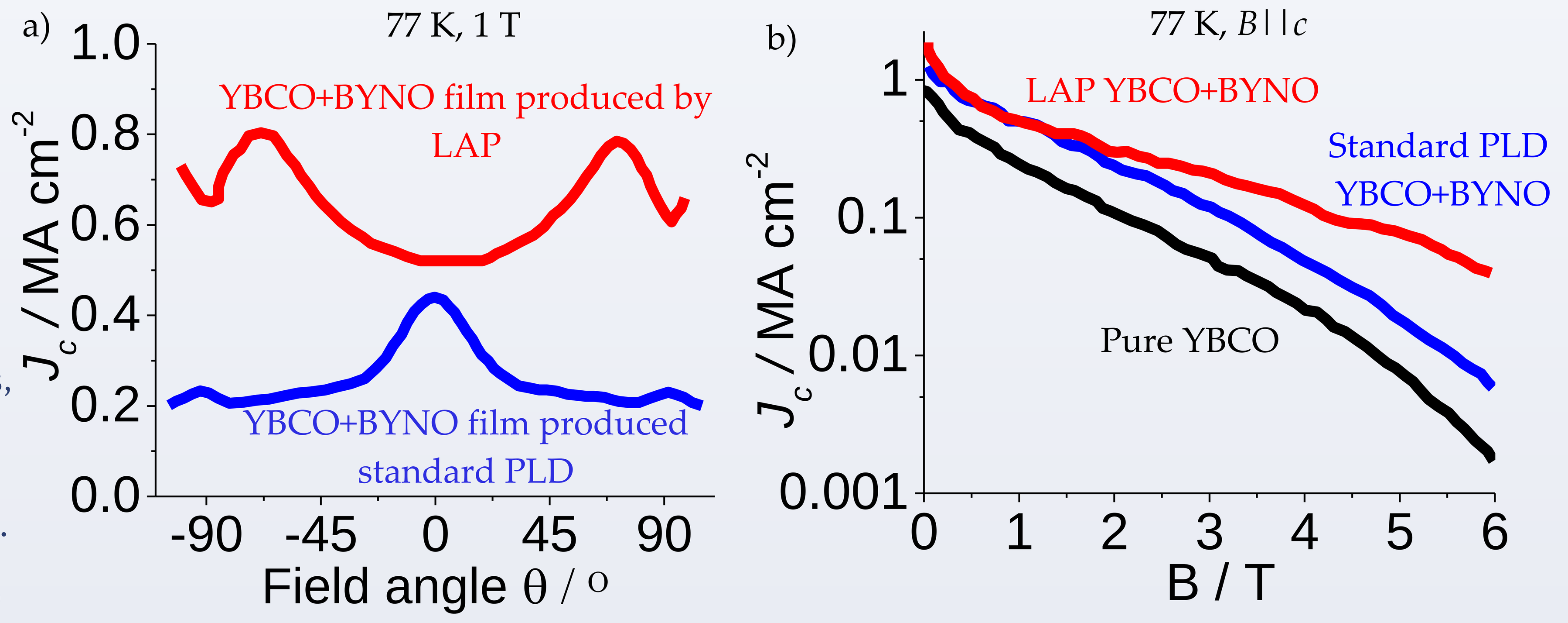
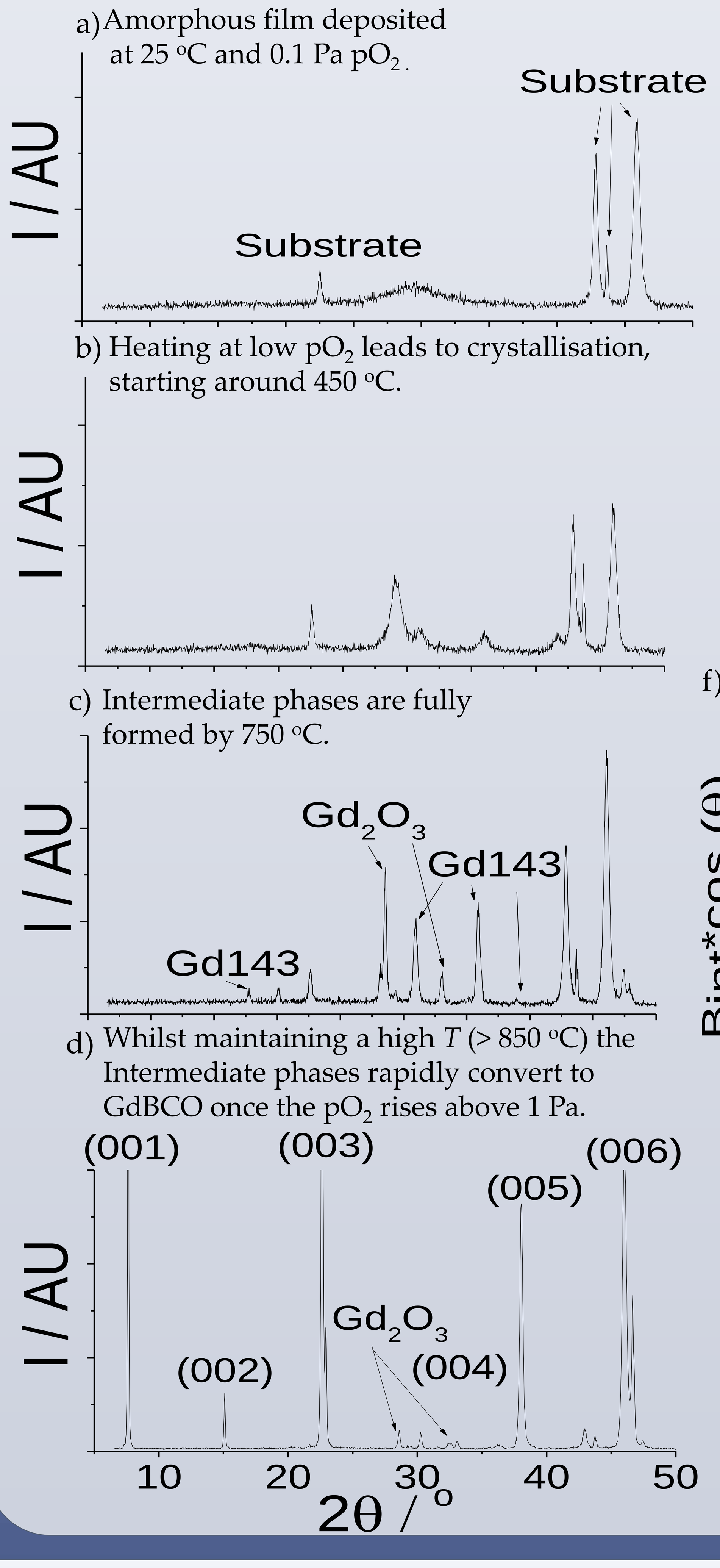
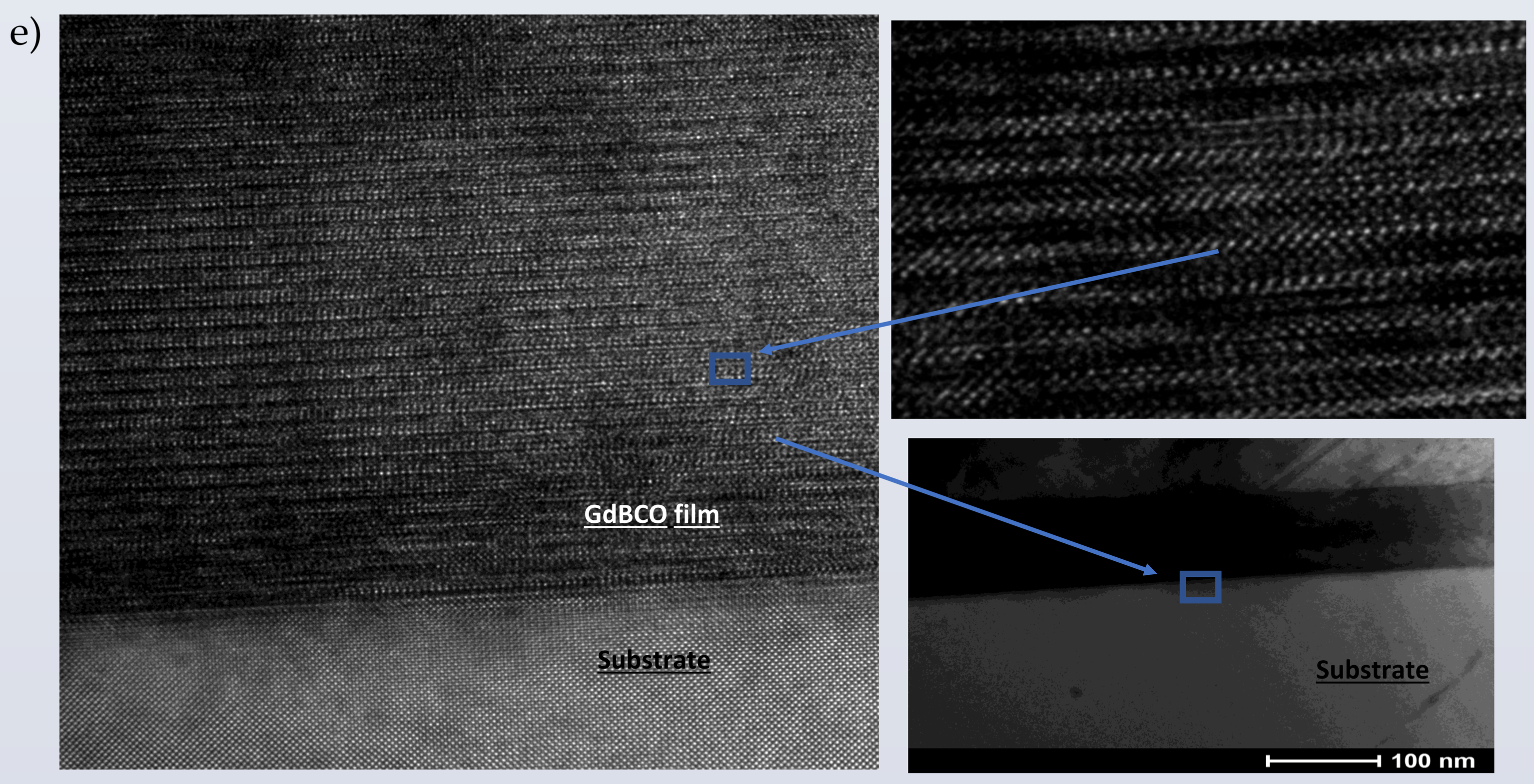


Figure 5. a) J_c vs angle and b) J_c vs field plots showing the strong performance of a in-situ LAP sample.

Ex-situ

- We have successfully replicated the RCE-DR process using PLD, rather than e-beam deposition. 0.75-1 μm thick GdBCO films, with strong epitaxy, high T_C's and a dispersion of Gd_2O_3 particles (see Fig 6) were produced. Important film formation was exceptionally fast with growth rates (> 1 μm/min).
- Three methods are being investigated into how to refine the Gd_2O_3 particles : 1) Using inoculants (e.g. Pt or Ce), 2) Using different rare-earths, 3) Using different Gd:Ba:Cu ratios to change the liquid:Gd_2O_3 ratio present in the film before GdBCO crystallisation.
- Current efforts have generated a variety of Gd_2O_3 particle sizes (as identified from Williamson-Hall plots) and an investigation into the effect of their size on J_c is ongoing.





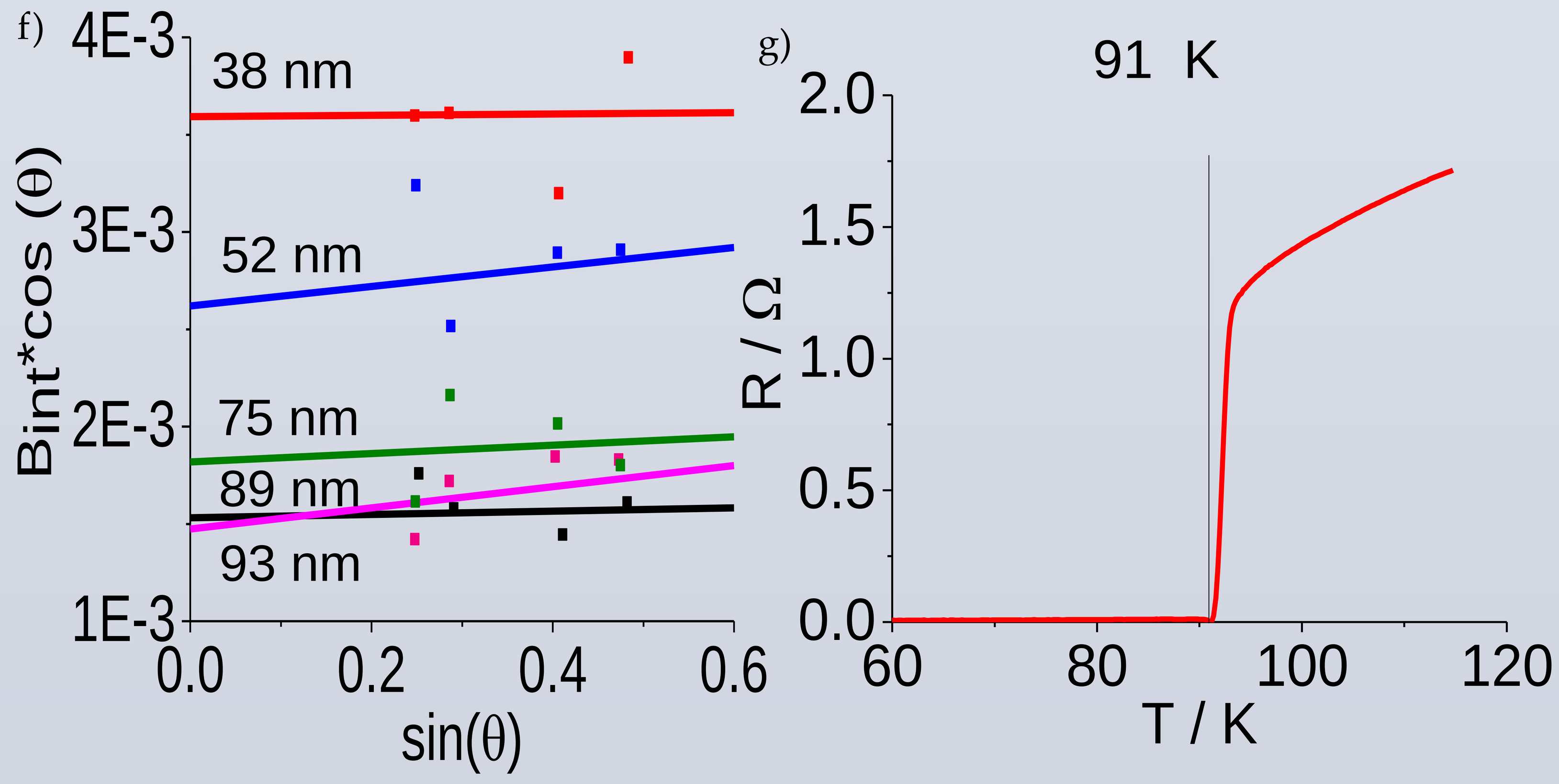


Figure 6. All data was collected on films of GdBCO + Gd_2O_3 grown by an ex-situ LAP process. a-d) XRD traces of films at various stages of the ex-situ processing route. e) TEM cross section showing a film with strong epitaxy, slight crystalline disorder and a remnant liquid layer on top. f) Williamson-Hall plot of 5 films with a variety of Gd_2O_3 particle sizes. g) Representative *R* vs *T* plot for these films, showing their high T_c (91 K).

5. Conclusions

To realise the dream of widespread coated conductor new methodologies are needed to produce tapes both fast and with high performance. Our study looks into trying to achieve this using both in-situ and ex-situ methods of liquid assisted processing, whilst simultaneously looking at ways to control and even design the microstructures to optimise their pinning characteristics. We have successfully created highly aligned high T_c films, at high rates, and with good J_c performance relative to standard PLD films.

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