IOP Publishing | Superconductor Science and Technology
Supercond. Sci. Technol. **33** (2020) 040301 (5pp) https://doi.org/10.1088/1361-6668/ab4ccd

Preface

Artificial pinning centers in (Y, RE)-Ba-Cu-O superconductors: recent progress and future perspective

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Introduction

A microscopic understanding of vortex pinning in type II superconductors began with the theoretical discovery of magnetic vortices by Abrikosov, which received the 2003 Nobel Prize in Physics [1, 2]. When type II superconductors are exposed to magnetic fields (H), the magnetic field enters as quantized vortices, each with a fundamental flux $\varphi_0 = 2.07 \times 10^{-11}$ T cm^{-2}, or 2.07×10^{-15} Wb. The vortex core size on the order of the superconducting coherence length can be very small, e.g. ~1–2 nm for the cuprate family of high-temperature superconductors (HTSs). The vortices electrically interact with each other by repelling, and act collectively together as a flux lattice that is affected by the intrinsic crystal lattice properties and microstructure defects. For superconducting power applications where applied magnetic fields are in the range of 0.1 T to >30 T, the areal number density of the vortices can reach incredibly high values. For example, for an applied magnetic field of 5 T, the vortex areal density is around 2.5×10^{11} cm^{-2}, which translates to inter-vortex spacing of about 20 nm (assuming a square lattice for vortices).

Somewhat surprisingly, if the crystal lattice for type II superconductors, such as HTS cuprates [3] is nearly perfect without any defects to pin vortices, the vortices can move collectively and almost freely in an applied magnetic field due to Lorentz forces, which results in electrical resistance at a fairly low critical current density $J_c(H, T)$ at an applied magnetic field (H) and temperature (T). In order to realize useful critical current densities in type II superconductors, imperfections and defects must be added to the crystal lattice to effectively pin vortices. The simplest example of this was achieved in the (Y, RE)$Ba_2Cu_3O_7$ (where RE is rare earth elements) family by depositing thin films, in which high densities of dislocations and other growth defects are added into the film microstructure and dramatically increase the critical current density J_c(77 K, $H//c$-axis) $> 10^6$ A cm^{-2} compared to J_c (77 K) $< 10^3$ A cm^{-2} for single crystals [4–6].

Artificial pinning centers

The research into artificial pinning centers (APCs) in HTS cuprates began shortly after discovery of the materials in 1986 [3]. For (Y, RE)$Ba_2Cu_3O_7$ materials, the addition of YBa_2CuO_5 (Y211) was considered for vortex pinning especially in the 1990s, but it was somewhat controversial whether increases of current density were from vortex pinning of Y211 additions or improved lattice structures [5]. Irradiation was shown to improve critical current densities of $YBa_2Cu_3O_7$ (YBCO); e.g. in a 1991 paper [4]. However the $J_c(H, T)$ increases were moderate.

The addition of nanophase defects, such as Y211 nanoparticles, into YBCO thin films was achieved from 2003 by several groups, with large increases of $J_c(H, T)$ [7–10]. Since then, intensive efforts were devoted to artificially generate secondary nanophases in the superconducting matrix for the different growth processes; pulsed laser deposition (PLD) [11–13], metal–organic chemical vapor deposition [14], and chemical solution deposition [15, 16].

It is generally understood that vortex pinning can be optimized in type II superconductors by adding ultra-high densities of defects into the crystal structure to match the number of vortices, and with sizes as close to the superconducting coherence length as possible. Precisely how this can be achieved is a fascinating and very complex experimental challenge, given the large number of superconductor processing methods used, and the hundreds of types of ultra-small defects demonstrated to be achievable. Theoretical modeling of the complex collective flux pinning phenomena has only recently achieved an initial understanding [17], and modeling studies are expected to remain limited for many years because of the difficulty of the work and large levels of computation power required.

Current status

Because of limited model understanding, the field of flux pinning in HTS cuprates has primarily progressed for over 30 years through thousands of Edisonian-type experimental studies. The general scientific field of flux pinning of HTSs is large, with 17 100 article citations since 1995 using the search term 'flux pinning high temperature superconductors' (Google Scholar, 19 August 2019).

The 14 papers in this Focus Issue present varying topics, including industrial processing, flux mechanisms for different pinning regimes at magnetic fields from 0–33 T and operation temperatures from 5 K to 90 K, and the optimization of different types of defects, such as $BaMO_x$ phases (M=Sn, Zr, Hf, etc) [18–31]. The collection of papers provides a current snapshot of experimental studies, and several reviews are provided. A topical review by Feighan *et al* focuses on one of the remaining problems—how to design pinning in second-generation HTS coated conductors, specifically those made using physical vapor deposition methods (and in particular PLD), through an understanding of the materials science [20]. The review presented the potential for rapid *ex situ*, liquid assisted growth, which is likely to be a necessary universal approach for applications where low cost is critical [20]. Finally, a semi-empirical analysis of the types of defects studied thus far is presented, especially on how they strongly increase $J_c(H, T)$ for three different regimes: (i) $T > 65$ K, $H < 1$ T; (ii) $T = 30$ K–65 K, $H \sim 1$–5 T; (iii) $T < 30$ K, $H > 5$ T. A review article by Huang and Wang provides a summary of magnetic pinning additions, which have differences and potentially advantages compared with defect pinning, as it pins the magnetic flux rather than the normal core vortices [21]. Four major pinning schemes including metal/YBCO, oxide/YBCO, nanocomposite/YBCO and nanoparticle-embedded/YBCO were reviewed, with some positive benefits [21].

C-axis aligned one-dimensional (1D) APCs remain the focus of many groups, as shown in the development of different 1D APCs (or nanorods) in different REBCO films through both experiments and modeling [18]. A study by Awaji *et al* finds that the low-temperature flux pinning behavior in 1D APCs introduced in Sm123 + 5.6 vol%$BaHfO_3$ (BHO) films can be described as strong 1D APC pinning in the low field, and the coexistence of collective pinning from both nanorod pinning and random pinning in the high field [18]. In the 'many-nanorod' state in the high temperature region above the delocalization temperature, double peaks in the pinning force density F_p curves appeared due to the coexistence of nanorod pinning and random pinning [18]. In the paper by Chepnikov *et al*, 2G HTS wires were fabricated in an industrial process by the PLD of $GdBa_2Cu_3O_7$ films doped with 6%, 12% and 18% (molar) of $BaSnO_3$ (BSO) and 6% (molar) of $BaZrO_3$ (BZO), and the $J_c(H, T)$ properties were systematically measured from 4.2 K to 77 K. For relatively high industrial processing rates, the 6% BSO-doped samples deposited at 560 and 375 nm min^{-1} and the 6% BZO-doped sample deposited at 750 nm min^{-1} showed up to an 80% improved critical current compared to the reference sample [19]. Yoshida *et al* reported a very high F_p of 1D APC/SmBCO up to 1.6 T N m^{-3} on single crystal substrates and 1.5 T N m^{-3} on metal substrates at 4.2 K. While *c*-axis aligned 1D APCs play a critical role in providing correlated pinning at H/c-axis, a pinning landscape with mixed APCs of different morphologies for strong and *H*-orientation independent pinning will require a microscopic design of APC microstructures. Towards this goal, Wu and Shi present an integrated study of modeling of elastic strain energy with considerations of APC/HTS interfacial strains and experimental demonstration of a mixed APC pinning landscape using microscale strain manipulation [30].

A review of flux pinning progress in (Y, RE)-Ba-Cu-O since 1995, and the impact for power applications, was studied by data mining in a topical review [32]. Development of strong APC HTS nanocomposites grown in solution-based processes is covered in both HTS films [25, 27] and larger scale coated conductors [22, 25] using solution processes that are potentially low cost. It is particularly worth mentioning that the suspension of pre-formed BZO and BHO nanoparticles (3D APCs) in high concentrations have been achieved to allow high-field applications of solution-processed coated conductors [25]. The 3D APCs have the advantage of providing a strong and isotropic pinning landscape as illustrated in the angular dependence of pinning by Palau *et al* [27]. A theoretical study of the pinning properties of the 3D APCs of different diameters in the range of two to four coherence lengths is presented by Willa *et al* to determine the limit of the applicability of the strong-pinning theory [29]. Different J_c–H behaviors are revealed on the 3D APCs at low and high concentrations. Considering the critical importance of experimentally controlling the 3D APC diameter in *in situ* processes, Sparing *et al* developed a PLD–inert gas condensation approach for the simultaneous control of the 3D BHO APC diameter and areal density in YBCO multilayers [28].

Impact and future directions

The field of (Y,RE)-Ba-Cu-O coated conductors for power applications was started in 1995, and manufacturing advances reached 1 km of length in ~2010. The addition of APCs in fully manufactured films began in ~2011, and has continually progressed since then, with many of the ~12 world-wide manufacturers studying different methods of APC additions. The implantation of flux pinning into (Y, RE)-Ba-Cu-O by manufacturers tries to duplicate the strong increases of $J_c(H, T, \theta)$ achieved in research laboratories. However, processing parameters in manufacturing can be different from that used in research; e.g. the deposition rates are typically much higher, which can strongly affect the microstructures achieved. Because of this, the $J_c(H, T, \theta)$ increases achieved by manufacturers are in general expected to be different from those in research laboratories.

The impact of $(Y, RE)Ba_2Cu_3O_7$ vortex pinning on improving applications can be substantial, and increases of $J_c(H, T, \theta)$ by 10–100 times have been achieved for varying temperatures and applied fields. The increases of the critical current density (or power density) can provide many benefits for power devices, including significantly higher performance, enabling operation at temperatures >50 K where cryocoolers have ∼100 times less weight and can be ∼10 times more energy efficient, and can enable new capabilities not achievable with $(Y,RE)Ba_2Cu_3O_7$ not optimized for vortex pinning. The increases of the critical current density (or power density) is especially critical for industries such as aerospace, defense or energy with new compact fusion schemes, where the cost–size-–weight–power–loss can determine or limit application viability and use.

While tremendous advances and improvements have been achieved so far with APCs, the advances do not follow the S-curve law of decreasing performance as time progresses. Some of the strongest advances of $J_c(H, T, \theta)$ from APC addition were achieved recently by several groups, by using novel and ultra-precise processing control of >10 vol% addition of defects [27, 33]. And the increases of $J_c(H,T)$ so far have generally only reached about 20%–30% of the upper limit of depairing current densities [34, 35]. Because of that, and the complexities of the microstructures and collective phenomena, it can be expected that with even more precise understanding and microscopic control, even further advances of $J_c(H, T, \theta)$ might be achievable. Such advances might come from nanoscale design engineering with DNA [36], or other techniques that might evolve over time.

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