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Vortex structure and magnetic properties of $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ single crystals

L Vinnikov¹, A Friedman², I. Felner³, A Troshina^{1,4}, Y Yeshurun²

¹ Institute of Solid State Physics, RAS, Chernogolovka, Russia

² Institute of Superconductivity, Bar-Ilan University, Ramat-Gan, Israel

³ Racah Institute of Physics, The Hebrew University, Jerusalem, Israel

⁴ Moscow State University, Moscow, Russia

E-mail: freidma@gmail.com

Abstract. Magnetic decoration of $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ revealed an hexagonal vortex lattice in overdoped single crystals ($x > 0.4$, $T_c = 14-18$ K). A disordered vortex lattice was observed in a crystals with optimal content of phosphorus ($x \approx 0.4$, $T_c = 25-30$ K). Magneto-optical studies and global magnetization measurement of the optimally-doped crystal have led to an estimated critical current density of $\sim 10^5 \text{ A/cm}^2$ at 5-12 K in fields up to 0.7 T. This high critical current density suggests strong pinning, probably due to defects, a result consistent with the observed disordered vortex lattice. The critical current density of the overdoped crystal is much smaller, i.e. $\sim 10^4 \text{ A/cm}^2$ at 5 K in fields up to 0.1 T, decreasing to virtually zero at 0.3 T.

1. Introduction

The pnictides, discovered in 2008 [1], provoked a great deal of interest owing to a series of unusual properties [2]. These materials share, as a common structural motif, superconducting FeAs or FeSe/Te layers. In most cases, superconductivity was induced by doping charge carriers into a stoichiometric parent compound which shows a collinear antiferromagnetic spin-density-wave ground state. The chemical doping was initially carried out only outside the FeAs layers, [3,4] with the electronic phase diagram resembling that of cuprate superconductors [5,6].

Later, however, it was found that even doping at the Fe site (with Co [7] or Ni [8]) could induce superconductivity. Numerous state-of-the-art experimental techniques developed for the cuprates have been applied to the study of these new families (for review articles see [9,10]). These materials with T_C values up to 55 K, are of great interest for applications due to their lower anisotropies and ultrahigh upper critical fields. Moreover, in the last years a significant progress has been made in the fabrication of iron-based superconducting wires and tapes using the powder-in-tube processing method [11]. It is thus clear that study of pinning and vortex structure in pnictides is of utmost importance for further development of wire technology and their exploitation in future devices.

The iron-based pnictide $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ system has recently attracted special interest for its potential large critical current. Its structure strongly depends on phosphorus content. For low doping ($x < 0.2$) and low temperatures, the material exhibits a spin-density wave state – which is equivalent to anti-ferromagnetic order in a metal. For higher doping the materials turn to be superconducting at lower temperatures [12]. There is an optimal doping level which exhibits maximal critical temperature T_C of about 30 K. Recently, it was suggested [13] that the charge state of the doped compounds has an important role in the mechanism of collective pinning in this materials [14]. This suggestion was based on the observation [15] of a sharp decrease (by several orders of magnitude) in J_C in phosphorus



underdoped and overdoped single crystals compared to the optimally-doped compound. This decrease in J_C signifies a strong decrease in the vortex pinning energy.

The goal of the work described here was to correlate the vortex structure in optimally-doped and overdoped samples with their critical current. The working assumption of the project was that the vortex lattice expected for a low- J_C material will change to a disordered structure for the high- J_C materials.

2. Experimental

Single crystals were received from Stanford University. The (nominally) optimally-doped crystals have critical temperatures T_c of 25-30 K. The overdoped and underdoped samples show T_c of 14-18 K. The weight of the crystals was estimated from their dimensions. For a reliable estimation of the dimensions we used scanning electron microscope.

The critical current, J_C , was measured exploiting both SQUID susceptometry for global magnetic measurements and magneto-optical technique for local magnetic imaging. The vortex structure in single crystals of $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ with different doping levels was studied by high resolution Bitter decoration technique, using magnetic nanoparticles [16]. Helium gas pressure was $\sim 2 \times 10^{-2}$ Torr. High resolution of about 100 nm was achieved owing to the small average size (< 10 nm) of the magnetic particles. Decorations have been performed at temperatures $T_d \leq 6$ K in applied magnetic fields of 80-200 Oe perpendicular to the 'as grown' surface namely, parallel to the c axis. The vortex structures were studied and analyzed by application of Delaunay triangulation and Fourier transformation, allowing estimation of the extent of ordering of each vortex structure.

3. Results and discussion

The left panel of figure 1A shows vortex structure in applied magnetic field of 80 Oe in an overdoped sample of $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ with $T_c \approx 18$ K. The central panel shows the same image following Delaunay triangulation computation. This figure is composed of bright and grey and black areas. The bright areas correspond to domains with 6 close neighbors generating regular vortex lattice whereas the grey and black areas correspond to defective domains with number of close neighbors other than 6. In the grey areas the coordination number is 5 or 7 and in black areas corresponds to other coordination numbers. Defects of the vortex lattice are mostly located on domains boundaries allowing estimation of the size of the domains. Ratio of the area of bright zones to the area of grey and black zones can be regarded as an extent of vortex lattice perfection. This ratio was found to be 0.45 for the data of figure 1. Figure 1B shows the isothermal magnetic moment measurements of the same sample at 5 K, indicating low critical current density of 10^3 - 10^4 A/cm² in zero field.

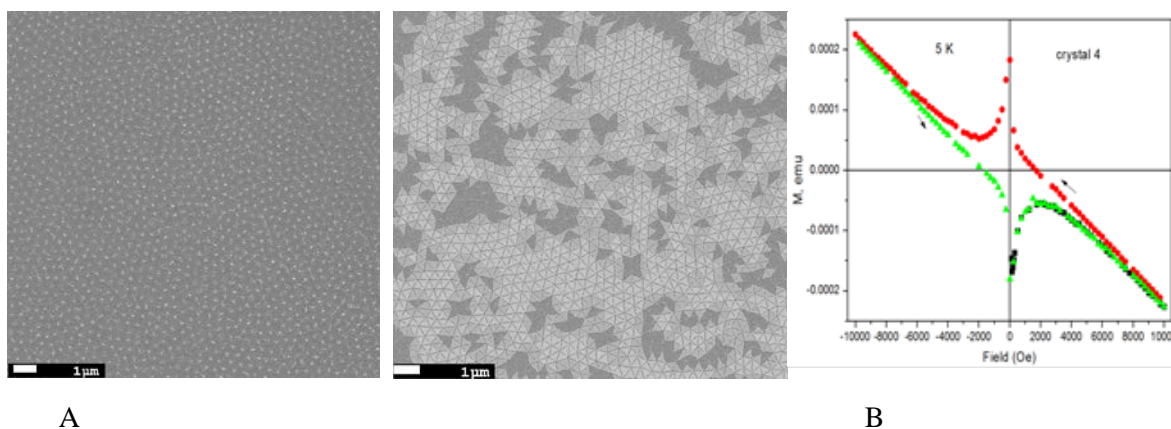


Figure 1. A. Left: Vortex structure at applied magnetic field of 80 Oe in the overdoped sample $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ ($T_c \approx 18$ K). **Right:** Delaunay triangulation of the same portion of structure. **B.** Magnetization loop of the same sample at $T=5$ K.

Figures 2A and 2B exhibit similar data for another overdoped sample, with $T_c \approx 14$ K. In this case, the ratio of the area of bright zones to the area of grey and black zones is 0.75 and J_C at 5 K in the range of 10^3 - 10^4 A/cm².

For an optimally-doped crystals ($T_c = 25$ K) the ratio of the areas of bright to grey and black zones was less than 0.25 (Fig. 3A) and estimation of J_C based on the measurements of magnetic moment of the same sample (Fig. 3B) yields $\sim 10^5$ A/cm² at 5 K and zero field. It is important to note that the ratios of the area of bright zones to the area of grey and black zones are different in different parts of the same crystal; this can be associated with heterogeneities of the phosphorus content (see below).

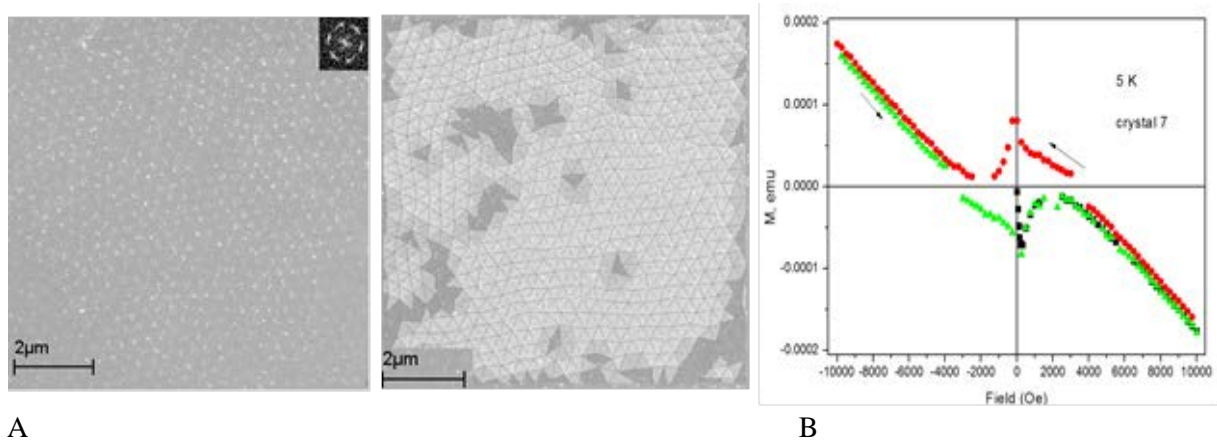


Figure 2. A. Left: Vortex structure at applied magnetic field of 80 Oe in the overdoped sample $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ ($T_c \approx 14$ K). **Right:** Delaunay triangulation of the same portion of structure. **B.** Magnetization loop of the same sample at $T=5$ K.

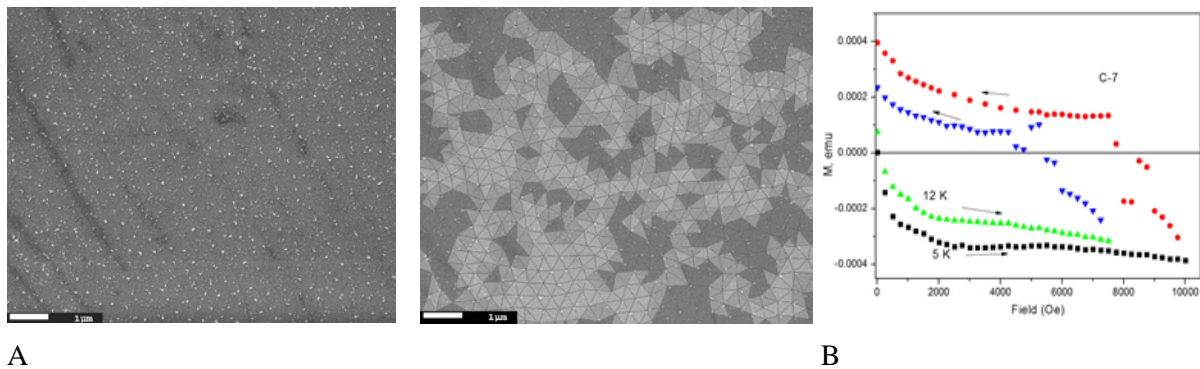


Figure 3. A. Vortex structure (left) and Delaunay triangulation (right) of a single crystal with optimal doping ($T_c \approx 25$ K) at applied magnetic fields 20 Oe. **B.** Magnetization loop of the same sample at $T=5$ K and $T=12$ K.

Figure 4A shows a magneto-optical image of optimally-doped crystal ($T_c = 25$ K) and profiles of magnetic field penetration (4B). Estimation of the critical currents density for this crystal, based on the magnetic field profiles, also yields a value of about 10^5 A/cm². The critical current density degrades slowly with increasing magnetic field and temperature [17].

The Fourier transforms of the vortex structures of two optimally-doped ($T_c = 25$ and 29 K) and an overdoped ($T_c = 14$ K) samples are shown in figure 5A, 5B, and 5C, respectively. While the Fourier transform of the overdoped crystal exhibits 6 well pronounced spots indicative of a regular triangular lattice, the optimally-doped crystals show a continuous circle that corresponds to arbitrary orientation of triangular elements.

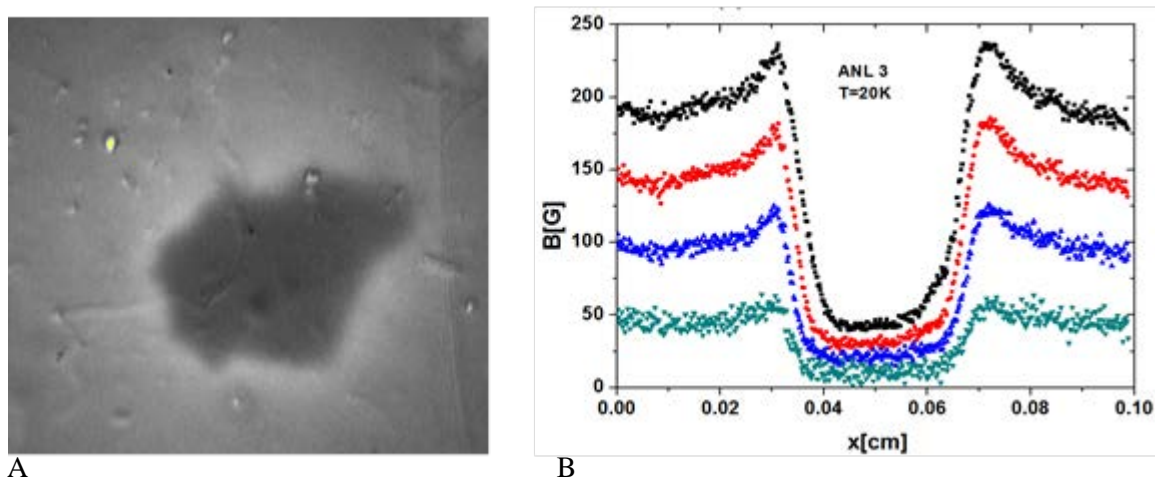


Figure 4. Magneto-optical image of optimally-doped crystal (A) and profiles of the magnetic field penetration (B).

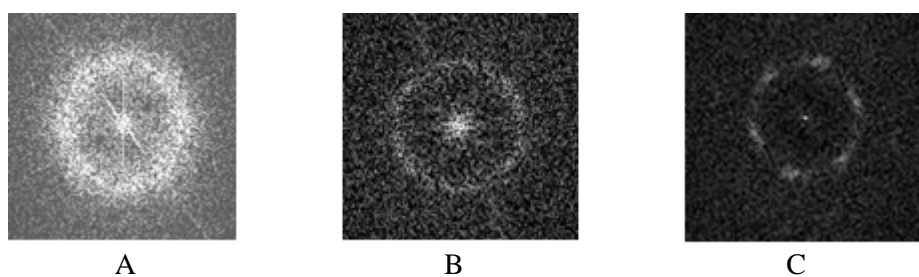


Figure 5. Fourier transforms of vortex structures of optimally-doped ($T_c = 25$, and 29 K) (A and B, respectively) and overdoped ($T_c = 14$ K) (C) samples.

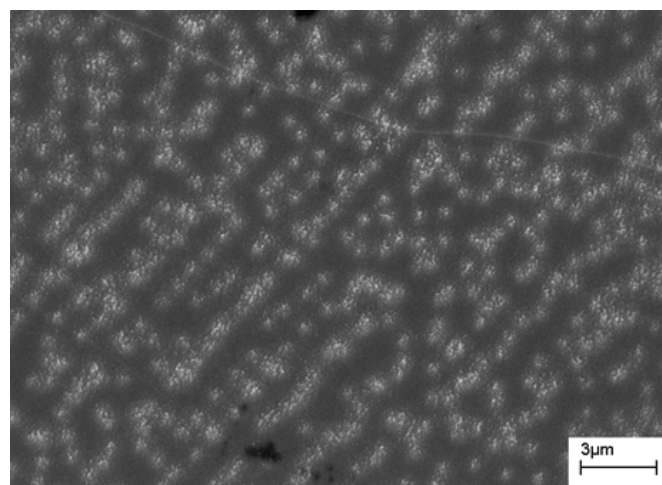


Figure 6. Vortex structure in optimally-doped $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ crystal in presumably underdoped area.

In crystals with optimal doping (nominally, $x = 0.4$) we observed certain areas with linear arrangement of vortices that can be related to twinning typical for underdoped crystals. Twinning in these crystals appears as a result of antiferromagnetic transition. Presence of underdoped areas can be

explained by heterogeneities of a phosphorus distribution that were frequently revealed by local X-ray electron probe analysis. As shown in figure 6, the vortices in these areas are situated on the twin boundaries that probably serve as pinning centers.

To summarize, the main finding of this work is the observation of large, well-ordered domains of regular triangular vortex lattice over tens of vortex lattice periods in overdoped $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ crystals. Such structure correlates with reduced critical currents density of these crystals. In optimally-doped crystals the size of ordered domains is only a few vortex lattice periods as in other pnictides [18,19] and in iron-containing chalcogenides [20] all characterized by high currents density.

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