

**Local measurement of the penetration depth in the pnictide superconductor Ba(Fe_{0.95}Co_{0.05})₂As₂**Lan Luan, Ophir M. Auslaender,* Thomas M. Lippman, Clifford W. Hicks, Beena Kalisky, Jiun-Haw Chu, James G. Analytis, Ian R. Fisher, John R. Kirtley, and Kathryn A. Moler[†]*Geballe Laboratory for Advanced Materials, Stanford University, Stanford, California 94305, USA and Stanford Institute for Materials and Energy Science, SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA*

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We use magnetic force microscopy (MFM) to measure the local penetration depth λ in Ba(Fe_{0.95}Co_{0.05})₂As₂ single crystals and use scanning superconducting quantum interference device susceptometry to measure its temperature variation down to 0.4 K. We observe that superfluid density ρ_s over the full temperature range is well described by a clean two-band fully gapped model. We demonstrate that MFM can measure the important and hard-to-determine absolute value of λ , as well as obtain its temperature dependence and spatial homogeneity. We find ρ_s to be uniform on the submicron scale despite the highly disordered vortex pinning.

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The magnetic penetration depth λ , one of the two fundamental length scales in superconductors,¹ characterizes many fundamental properties. It evaluates the phase stiffness of the superconducting state by the temperature $T_{\theta}^{\max} \propto 1/\lambda^2$ at which phase order would disappear.² It also determines the superfluid density $\rho_s = 1/\lambda^2$, the number of electrons in the superconducting phase. However, its absolute value is notoriously difficult to measure, especially in samples that may have either intrinsic or extrinsic inhomogeneity. In this Rapid Communication, we will report a technique to measure λ by magnetic force microscopy (MFM). The advantage of using local probes over bulk techniques is that they allow us to study the sample homogeneity. We implement this technique to determine ρ_s in a iron-pnictide superconductor Ba(Fe_{0.95}Co_{0.05})₂As₂.

Iron-pnictide superconductors have been under extensive study since their recent discovery.³ The high transition temperature,⁴ the proximity to a magnetic state,⁵⁻⁷ and the existence of multiple conducting bands^{8,9} combine to make it difficult and interesting to resolve key issues such as the superconducting order-parameter (OP) symmetry,^{10,11} the pairing mechanism¹² and the role of impurities and inhomogeneity.¹³ Those problems can be studied by measuring ρ_s . When the gap has nodes, $\rho_s(T)$ varies as a power law in T at low T , as demonstrated in YB₂Cu₃O_{7- δ} ,^{14,15} while a fully gapped OP gives a low- T exponential dependence.¹⁶ Since it is difficult to determine λ , its temperature variation $\Delta\lambda(T) \equiv \lambda(T) - \lambda(0)$ is often measured, which follows the same temperature dependence as ρ_s at low T . Sometimes this approach is sufficient, e.g., linear $\Delta\lambda$ in clean LaFePO over a wide temperature range provides strong evidence of well-formed line nodes.^{17,18} However, in the Ba-122 family, a steep power law $\Delta\lambda$ was obtained in the Co-doped compounds¹⁹ while an exponential ρ_s was measured in the K-doped materials.²⁰ The question waiting for clarification is whether different dopants lead to different OP structure. $\Delta\lambda$ measurement cannot infer OP symmetry except for $T \ll T_c$, but for multiband pnictides, the low- T regime may be dominated by the small-gap regions of the Fermi surface and may be altered by interband impurity scattering.²¹ It is thus important to measure the absolute value of λ to determine ρ_s over the full temperature range.

In this Rapid Communication, we measure the local $\Delta\lambda_{ab}(T)$ and $\lambda_{ab}(T)$, the penetration depth for screening currents flowing in the a - b planes, in electron-doped Ba(Fe_{1- x} Co _{x})₂As₂ single crystals ($x \approx 0.05$, $T_c = 18.5$ K, grown from self-flux⁶) from $T = 5$ K to T_c by MFM (Fig. 1). We use scanning superconducting quantum interference device (SQUID) susceptometry (SSS) (Ref. 22) to measure $\Delta\lambda_{ab}(T)$ down to 0.4 K. We find that ρ_s can be well described by a two-band fully gapped OP over the full temperature range. We also use MFM to image and manipulate vortices to measure the homogeneity of $\lambda_{ab}(T)$ and the flux pinning force. We find that ρ_s is uniform to within 10% or better although vortex pinning is highly inhomogeneous.

In our MFM, a sharp magnetic tip at the end of a flexible cantilever faces the crystal surface, which is parallel to the a - b plane. By measuring the shift in the cantilever's resonant frequency,²³ we determine $\partial F_z / \partial z$,²⁴ where F is the force between the tip and the sample, and \hat{z} is along the tip magnetization direction and is normal to the cantilever and to the crystal a - b surface. $\partial F_z / \partial z$ changes abruptly within a few nanometers of the surface, allowing precise determination of the tip-sample separation z . In the Meissner state, the tip-superconductor interaction can be approximated by the magnetic interaction between the tip and its image mirrored through a plane at $z = -\lambda_{ab}$ [Fig. 1(a) inset].²⁵ This local levitation force is determined uniquely by $z + \lambda_{ab}(T)$ for $z \gg \lambda_{ab}$ (λ_c does not enter for any source field above a smooth infinite ab surface).²⁶ Thus, changing T at constant z offsets a $\partial F_z / \partial z$ curve along the \hat{z} axis by $\Delta\lambda_{ab}(T)$. To acquire the data labeled as MFM $\Delta\lambda$ in Fig. 2, we park the tip at $z = 500$ nm, change T and acquire $\partial F_z / \partial z$. The z offset required to match $\partial F_z(T) / \partial z$ with a reference curve at $T = 5$ K gives $\lambda_{ab}(T) - \lambda_{ab}(5$ K). Using a similar method for data acquired by SSS in a ³He refrigerator,¹⁸ we extend measurements of $\Delta\lambda$ down to 0.4 K on two nominally identical samples. The SSS results match the MFM results over the common temperature range. By using local scanning probes, we reduce the influence of the complex topography around the sample edges.²⁶

Figure 2 shows that $\Delta\lambda_{ab}(T)$ increases very slowly with T at low T , inconsistent with the linear dependence that would be expected for line nodes. The same behavior appears at

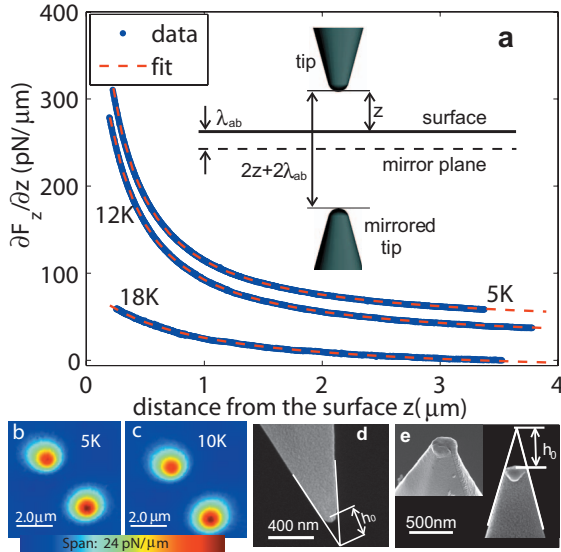


FIG. 1. (Color) Technique to measure λ and $\Delta\lambda$ by MFM from (a) Meissner repulsion and [(b) and (c)] vortex imaging. (a) z dependence of $\partial F_z/\partial z$ (blue symbols) at $T=5, 12$, and 18 K and the fit to the truncated cone model (red dashed line). (Inset) Sketch to illustrate that the tip-superconductor interaction in the Meissner state can be approximated by the interaction between the tip and its image mirrored through a plane (dashed line) λ_{ab} below the surface of the superconductor (solid line) when $z \gg \lambda_{ab}$. Comparing the curves provides $\Delta\lambda_{ab}$ independently of the tip model. Fits give $\lambda_{ab}(T)$ at $T=5, 12, 18$ K to be $0.33, 0.37, 1.10$ μm . [(b) and (c)] Images of two vortices ($z=400$ nm) at (b) 5 and (c) 10 K. The similar shapes and amplitudes of the images show that both the spatial variation and the temperature-induced change in λ_{ab} are small. [(d) and (e)] Scanning electron microscopy images of the tip (d) before and (e) after the measurements. An accidental crash during the measurement changes the truncation distance h_0 from (d) 300 ± 30 nm to (e) 400 ± 20 nm. Despite the crash, $\partial F_z/\partial z$ curves taken before and after the crash give the same $\lambda_{ab}(5$ K) to within 10 nm.

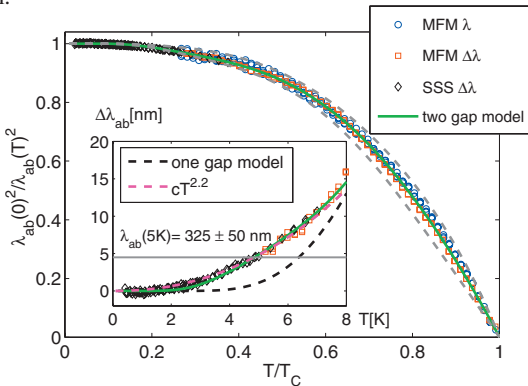


FIG. 2. (Color) Normalized superfluid density $\rho_s(T)/\rho_s(0) \equiv \lambda_{ab}(0)^2/\lambda_{ab}(T)^2$ vs T . We determine $\Delta\lambda_{ab}(T)$ by MFM (squares) and by SSS (diamonds) from measuring the change in the diamagnetic response at fixed height. These values are offset to match the absolute value of $\lambda_{ab}(T)$ obtained by fitting the MFM data to the truncated cone model (circles). The green solid line shows a fit of the two-band s -wave model discussed in the main text ($\Delta_1=2.6T_c$, $\Delta_2=0.8T_c$, $x=0.88$, and $a=1.4$). The width of the dashed band reflects the uncertainty in $\lambda_{ab}(0)$. Inset: $\Delta\lambda_{ab}$ vs T at low T . Black dashed line: one-gap s -wave model with $a=1.5$ and $\Delta_0=1.95T_c$. Magenta dashed line: $\Delta\lambda_{ab}(T)=cT^{2.2}$ ($c=0.14$ nm/ $\text{K}^{2.2}$).

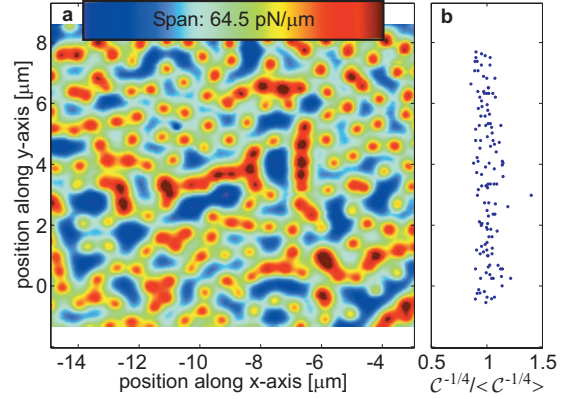


FIG. 3. (Color) Spatial uniformity of λ_{ab} from vortex imaging at 5 K. (a) Image of vortices at $T=5$ K, $z=125$ nm, and a vortex density giving 3.5 mT. (b) The normalized length scale associated with each vortex peak in (a) $C^{-1/4}/\langle C^{-1/4} \rangle$ ($\langle \rangle$ denotes the mean). We find $C^{-1/4}=250(1 \pm 0.08)$ nm (70% confidence interval).

three different locations on two samples with SSS and at four different locations with MFM on a third sample. Between $T=0.02T_c$ and $0.4T_c$ $\Delta\lambda_{ab}(T)$ varies by about an order of magnitude less than has been reported for a similar sample using a bulk technique.¹⁹ At low T , $\Delta\lambda_{ab}(T)$ can be described by either a two-band fully gapped model or by a power law with a small coefficient as described below.

We also extract $\lambda_{ab}(T)$ by modeling the tip-superconductor interaction, with the magnetic tip as a sharp single domain cone truncated at distance $h_0=400 \pm 20$ nm from its apex as shown in Fig. 1(e). Within the model, the z dependence of $\partial F_z/\partial z$ is given by

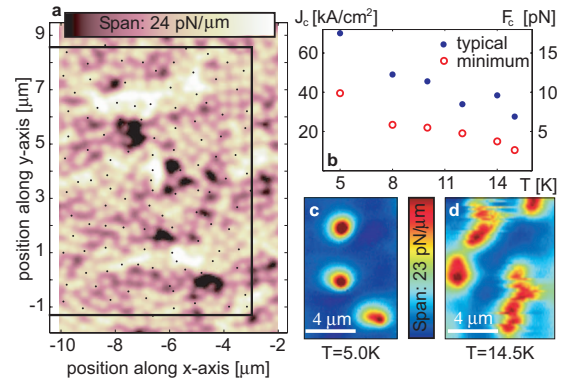


FIG. 4. (Color) Inhomogeneous vortex pinning. (a) Image of vortices at $T=5$ K, $z=80$ nm, and $B=9.5$ mT, overlaid by the vortex positions (dots) in Fig. 3(a) and the boundary of that scan (black frame). The vortex configuration is highly disordered. Vortices avoid the same regions in both scans, taken days apart and many thermal cycles apart. (b) Local critical current (left ordinate) and the depinning force (right ordinate) vs T . The comparison of minimum and typical values implies inhomogeneous pinning. (c) Image of vortices at $T=5$ K, $z=120$ nm showing that F_{\min} only moves the vortex at the bottom. (d) Image of moving vortices at $T=14.5$ K, $z=430$ nm showing that F_{typ} allows us to drag all vortices a distance of several microns.

$$\frac{\partial F_z(z, T)}{\partial z} - \partial F_z(z, T) / \partial z \Big|_{z=\infty} = A \left\{ \frac{1}{z + \lambda_{ab}(T)} + \frac{h_0}{[z + \lambda_{ab}(T)]^2} + \frac{h_0^2}{2[z + \lambda_{ab}(T)]^3} \right\}, \quad (1)$$

where A is determined by the tip shape and the coating. The value $A=78$ pN from fitting at $T < T_c/2$ is consistent to within 30% with the magnetic moment expected from the nominal iron coating on the tip and with that inferred from the tip-vortex interaction.²⁴ We record $\partial F_z / \partial z$ as a function of z and T and extract λ_{ab} at many temperatures by fitting to Eq. (1) with A and h_0 fixed and λ_{ab} and $\partial F_z / \partial z(\infty, T)$ allowed to vary separately for each T . The fit works well for all T (Fig. 1). The resulting values of $\lambda_{ab}(T)$ are shown in Fig. 2 with label ‘‘MFM λ ’’ and agrees well with the model-independent $\Delta\lambda$. If we consider only statistical errors, we obtain $\lambda_{ab}(5 \text{ K})=325 \pm 5$ nm with 70% confidence interval. However, the systematic error from the finite width corrections of the tip geometry is 5%. In addition, the ± 20 nm uncertainty on h_0 leads to $74 \leq A \leq 81$ pN by bootstrapping. The extremals of A and h_0 give ± 35 nm systematic error on $\lambda_{ab}(5 \text{ K})$. Thus, adding the two main sources of systematic error, we find $\lambda_{ab}(5 \text{ K})=325 \pm 50$ nm.

Knowing $\lambda_{ab}(T)$ gives ρ_s over the full temperature range (Fig. 2). The fact that ρ_s does not saturate at low T is inconsistent with a single-band isotropic gap. A two-band fully gapped OP, which was proposed theoretically^{10,11} and tested experimentally,^{8,20} describes the data well (Fig. 2). In the model, $\rho_s(T)=x\rho_1(T)+(1-x)\rho_2(T)$: $\rho_{1,2}(T)$ are the superfluid densities in bands $i=1, 2$, with gaps $\Delta_i(T)=\Delta_i(0)\tanh[\frac{\pi T_c}{\Delta_i(0)}\sqrt{a_i(\frac{T_c}{T}-1)}]$; a_i describes the rate of $\Delta_i(T)$ increasing upon cooling from T_c .¹⁶ Our fit [taking into account the systematic error on $\lambda_{ab}(5 \text{ K})$] gives $\Delta_1(0)=2.5 \pm 0.3T_c$, $\Delta_2(0)=0.70 \pm 0.1T_c$, $x=0.89 \pm 0.06$, and $a_1=1.45 \pm 0.4$ with $a_2 \equiv 1$. The value of a_1 suggests that pairing is likely to be more complicated than phonon-mediated weak coupling,^{12,27} which would give $a=1$. The magnitude of $\Delta_{1,2}(0)$ is consistent with the scaled down values deduced from optical spectroscopy on similar materials with higher T_c .^{8,9} At low T a power law cT^n , where $n=2.2$ and $c=0.14$ nm/K^{2.2} also fits the data. The dominant sources of errors are the calibration accuracy of the scanner, thermal drift, and the breakdown of the assumption of $z \gg \lambda_{ab}$, which together would bound c between 0.12 and 0.18 nm/K^{2.2}. The small coefficient is inconsistent with that previously reported.¹⁹ We rule out a nodal OP model since the impurity scattering rate required for such a model²⁸ to match our data is much higher than that reported in previous works on d -wave cuprates with deliberately added impurities.^{29,30} Instead, we interpret this weakened exponential behavior of $\Delta\lambda_{ab}$ and $\rho_s(T)$ from 0.4 K all the way to T_c as strong evidence for two full gaps, consistent with the extended s -wave OP.^{10,31}

We repeated the touchdown measurement at four positions separated by around 10 μm and obtained $\lambda_{ab}(T=5 \text{ K})=325, 330, 325,$ and 330 nm. This result suggests that λ_{ab} is uniform across the sample.

A second test of uniformity is afforded by measuring the

local T_c by mapping the lowest T at which we cannot detect Meissner levitation by MFM [sensitivity corresponds to $\lambda_{ab}(T) > 3 \mu\text{m}$] or diamagnetic response by SSS [sensitivity corresponds to $\lambda_{ab}(T) > 20 \mu\text{m}$ (Ref. 32)]. We find the variation in T_c to be less than 0.5 K throughout the range of $10 \times 10 \mu\text{m}^2$ by MFM and $200 \times 200 \mu\text{m}^2$ by SSS.

Vortex imaging provides a third test of $\rho_s(T)$ uniformity. To this end, we cool the sample in an external magnetic field and scan the tip at a constant height z above the surface at 5 K. All vortices appear very similar [Fig. 3(a)], indicating that the spatial variation in λ_{ab} is limited. The convolution of the tip and the vortex field makes it difficult to extract λ_{ab} from the vortex imaging. Instead, we calculate the normalized curvature at each vortex peak to quantify the spatial variation: $C \equiv \max(\partial F_z / \partial z)^{-2} \det(\frac{\partial^2(\partial F_z / \partial z)}{\partial x_i \partial x_j})$ (i, j run over 1, 2 and $x_1 \equiv x, x_2 \equiv y$). The length scale, $C^{-1/4}$, characterizes the spatial extent of the magnetic field from each vortex [Fig. 3(a)]. The scatter [Fig. 3(b)] of the normalized $C^{-1/4}$ ($\pm 8\%$) at constant z gives an estimate for the spatial variation in λ_{ab} .

In contrast to the uniform ρ_s , vortex pinning is very inhomogeneous. Vortices do not form an ordered lattice when field-cooled in fields up to 13 mT, the highest field that allows us to resolve individual vortices in this material. Instead, vortices always appear in the same regions when we thermal cycle in different fields using different cooling rates [Fig. 4(a)]. This behavior suggests inhomogeneous pinning. To measure the pinning force distribution, we use the MFM tip to drag individual vortices and to convert the recorded $\partial F_z / \partial z$ to the required force.²⁴ We measure two different forces [Fig. 4(b)]: the force for dragging the most weakly pinned vortex, F_{\min} , a measure of the smallest pinning force [Fig. 4(c)]; and the force for dragging all of the vortices (usually ≤ 10) in a field of view, F_{typ} , a measure of the typical pinning force [Fig. 4(d)]. In this sample $2 \leq F_{\text{typ}}/F_{\min} \leq 4$. $F_{\text{typ}} \approx 18$ pN at 5 K, corresponding to a critical current of $J_c \approx 80$ kA/cm² ($F_c = J_c \Phi_0 d$, where Φ_0 is the flux quantum, $d=10 \mu\text{m}$ is the sample thickness), consistent with the value from bulk measurement of an optimally doped sample.³³ Even at F_{typ} , vortices do not follow the tip all the way, indicating the existence of pinning forces larger than F_{typ} . In fact, F_{typ} is still at least an order of magnitude smaller than the force required to stabilize vortices in the dense clusters we see (the vortex-vortex interaction for a pair separated by 400 nm corresponds to a current density of 3 MA/cm²). We do not detect any correlation between pinning and superfluid density, suggesting that strong pinning exists without affecting superconductivity on the scale of λ_{ab} . The ability to measure the absolute value of the penetration depth despite a disordered vortex configuration is important since the most commonly used method, muon-spin-rotation,³⁴ assumes an ordered vortex configuration.

To conclude, by measuring $\lambda_{ab}(T)$ and $\Delta\lambda_{ab}(T)$ locally we find that underdoped Ba(Fe_{1-x}Co_x)₂As₂ ($x \approx 0.05$) has homogenous ρ_s whose temperature dependence can be described by a two-band fully gapped OP. This result provides thermodynamic evidence for fully gapped models such as the proposed extended s -wave model^{10,11} for Co-doped 122

pnictides and shows that it has the similar OP structure as the K-doped, despite the different dopants and substitution sites. We obtain $\lambda_{ab}(0) = 325 \pm 50$ nm, which gives $T_{\theta}^{\max} = A(\hbar c)^2 a / (16\pi e^2 \lambda^2) \approx 260$ K, where $a = \sqrt{\pi} \xi_c$, $\xi_c = 1.1$ nm,³⁵ and $A = 2.2$ in the three-dimension limit.^{2,33} $T_{\theta}^{\max} \gg T_c$, hinting that phase fluctuations are not as important here as in the underdoped cuprates.² Instead, T_c in the underdoped iron-pnictides may be suppressed by the competition with nonsuperconducting phases. MFM allows us to obtain the superfluid density and to map its spatial variation down

to the submicron scale. This capability may be useful to study how different phases compete for charge carriers.

Recently, we became aware of Nazaretski *et al.*'s work on MFM measurement of the penetration depth in a Nb film.³⁶

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