A temperature-modulated dilatometer by using a piezobender-based device

Yanhong Gu,1,2 Bo Liu,1,2 Wenshan Hong,1,2 Zhaoyu Liu,1,3 Wenliang Zhang,1,4 Xiaoyan Ma,1,2† and Shiliang Li1,2,5†

1Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China
2School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100190, China
3Department of Physics, University of Washington, Seattle, WA 98195, USA
4Swiss Light Source, Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
5Songshan Lake Materials Laboratory, Dongguan, Guangdong 523808, China

We report a new design of temperature-modulated dilatometer, which obtains the linear thermal expansion coefficient by measuring the oscillating changes of the sample’s length and temperature by a piezobender and a thermocouple, respectively. Besides the thermal expansion, it is also possible to obtain the Grüneisen parameter in a straightforward way without the knowledge of the heat capacity. Using an iron-based superconductor KFe$_2$As$_2$ as an example, we show that this device is able to measure thin samples with high resolutions at low temperatures and high magnetic fields. Despite its incapability of giving absolute values, the new dilatometer provides a high-resolution low-cost method to study many important physical properties in condensed matter physics, such as thermal and quantum phase transitions, and vortex dynamics in the superconducting state. The prototype design of this device can be further improved in many aspects to meet particular requirements.

I. INTRODUCTION

The thermal expansion of a material describes the variation of its length or volume with temperature and is an fundamental thermodynamical parameter in studying the physical properties of solids [1]. Especially, studying the change of thermal expansion across a phase transition has become one of the important techniques in condensed matter physics since it can reflect the intrinsic change of the electronic system with very high resolution [2–6]. In the case of studying superconductors, the thermal-expansion measurement can detect phase transitions and vortex dynamics within the superconducting state [7–10], which shows its unique advantages compared to resistivity and magnetic-susceptibility measurements. The ratio between the thermal expansion and the specific heat gives the Grüneisen parameter, which is a crucial thermodynamical parameter for studying quantum critical transitions [11–16].

For low-temperature measurements in the field of condensed matter physics, the mostly used and accurate dilatometers are based on directly measuring the length change of a sample with temperature by a plate capacitor [17–23]. The linear thermal-expansion coefficient $\alpha$ can be directly derived from $\Delta L/L = \alpha T$, where $L$ and $T$ are the length and temperature of the sample, respectively. Using alternating-current (AC) heating method, the thermal expansion can also be measured by temperature-modulated dilatometers (TMD), but previous reports only show measurements above room temperature [24–25]. The advantage of the TMD is that the setup is simple and the cost is low. The difficulty is how to measure the alternating length change of a sample at low temperatures.

In this work, we present a new design of TMD based on a piezobender device that can be used at low temperatures and high magnetic fields. It is based on the uniaxial pressure device as reported previously [26, 27]. With slightly changing the setup, we find that the device can be easily adapted to measure the linear thermal expansion. This method is similar to the temperature-modulated calorimetry (TMC) [28, 29]. The basic principle is to periodically heat a sample so that the oscillating changes of a sample’s length and temperature, i.e., $\Delta L$ and $\Delta T$, can be simultaneously determined with the assistance of a lock-in system. High resolutions can be thus achieved because of the capability of detecting small signals by the lock-in system. The linear thermal expansion $\alpha$ can be directly obtained as $\Delta L/L\Delta T$. We will use the iron-based superconductor KFe$_2$As$_2$ as an example to show the ability of our device of measuring the thermal expansion at low temperatures and high magnetic fields.

II. EXPERIMENTAL SETUP AND MEASUREMENT PRINCIPLES

Figure 1(a) shows the sketch of the AC dilatometer, which is similar to the uniaxial pressure device reported previously [26]. It is composed of a piezobender and a CuBe frame with two ends of a thin-slab sample attached on top of them. There are three contacts for the piezobender and two side ones are soldered together. In using it as a uniaxial pressure device, a DC voltage is applied to the piezobender, which will tend to move it due to the reverse piezoelectric effect and thus provide a force on the sample. To measure the thermal expansion, a heater and a thermometer are attached to two

---

[Note: The text contains scientific abbreviations and technical terms typical of condensed matter physics and material science, which are not translated for brevity.]
The two ends of the sample are attached to the CuBe frame and piezobender by glue. A heater and a thermometer are attached to the two sides of the samples. The measurement diagram of the AC dilatometer is shown in Fig. 1(b). The setup in Fig. 1(a) was put on the regular sample puck of the Physical Properties Measurement System (PPMS, Quantum Design), which provides the low-temperature and magnetic-field environment. A lock-in system was put on to the regular sample puck for the comparison of the waveforms of $V_{\text{sine out}}$ and input channels of the lock-in amplifier, respectively. (c) The comparison of the waveforms of $V_{\text{sin}}$ and $V_{\text{in}}$ (black line) and $V_{\text{sin}}$ (red line). The frequency of the sinout voltage of the lock-in amplifier is 1 Hz. The temperature is 5 K. A preamplifier with 1000 gain has been used. (d) Temperature dependence of the specific heat for KFe$_2$As$_2$ at 0 (black squares) and 5 (red circles) Tesla.

Neglecting all the phase differences, the linear expansion coefficient $\alpha$ is thus

$$\alpha = \frac{\Delta L_{AC}}{L_0 \Delta T_{AC}} = \frac{\eta \kappa \Delta V_{PB}}{L_0 \Delta T_{AC}},$$

which is the case for most traditional AC calorimeters.

The oscillating temperature of the sample will simultaneously cause the oscillation of its volume. The change of the length along a particular direction can be measured by the piezobender for the setup in Fig. 1(a) since the movement of the top will create a voltage that can be detected by the lock-in system. Figure 1(c) shows an example, where $V_{\text{sin}}$ is the sine output voltage of the lock-in amplifier while $V_{PB}$ is the voltage of the piezobender. It is clear that the periodicity of $V_{PB}$ is twice that of $V_{\text{sin}}$. The coefficient $\kappa$ is the relationship between the moving distance of the top of the piezobender and the voltage resulted from, which has been independently determined to be about (43.5 + 0.48T) nm/V below 10 K [30]. The value of $\eta$ is hard to determine and we will give a rough estimation by comparing our results with those measured in the capacitive dilatometer.

The sample used here is an iron-based superconductor KFe$_2$As$_2$. At $T_c = 3.4$ K, its thermal expansion along the a axis direction shows a drastic jump, changing from positive to negative value [6]. We grew the KFe$_2$As$_2$ samples by the flux method as reported previously [31]. The specific heat shows a clear superconducting transition at 0 T, which disappears at 5 T, as shown in Fig. 1(d). A slice of the sample for the thermal-expansion measurements was cut along the a axis with the length, width and thickness as 4 mm, 2 mm, and 18 $\mu$m, respectively. Two electronic contacts were made on the sample by silver epoxy. Because the resistance of the sample is very small (< 10$^{-3}$Ω), it is the contact resistances that actually work as the heater. Two other KFe$_2$As$_2$ samples have also been used to study the magnetic field dependence of $\Delta L$. 

$$\Delta T_{AC} = \frac{P_{AC}}{2 \omega C_s} \left[ 1 + \frac{1}{4 \omega^2 \tau_1^2} + 4 \omega^2 \tau_2^2 + \frac{2 K_b}{3 K_s} \right]^{-\frac{1}{2}},$$

where $C_s$ is the heat capacity of the sample, $\tau_1$ is the relaxation time from sample to bath, $\tau_2$ is associated with the time which the sample, the heater and the thermometer attain thermal equilibrium. The frequency-independent term $2K_b/3K_s$ is the geometric correction due to the finite thermal diffusivity of the sample. In the case where $\tau_1$ is large while $\tau_2$ and $2K_b/3K_s$ are small, $\Delta T_{AC}$ can take the much simpler form as

$$\Delta T_{AC} = \frac{P_{AC}}{2 \omega C_s},$$

FIG. 1. (a) Sketch of the sample holder for AC dilatometer. The two ends of the sample are attached to the CuBe frame and piezobender by glue. A heater and a thermometer are attached to the two sides of the samples. (b) Measurement diagram of the AC dilatometer. O and S1/S2 represent the sinout and input channels of the lock-in amplifier, respectively. (c) The comparison of the waveforms of $V_L$ (black line) and $V_{\text{sin}}$ (red line). The frequency of the sinout voltage of the lock-in amplifier is 1 Hz. The temperature is 5 K. A preamplifier with 1000 gain has been used. (d) Temperature dependence of the specific heat for KFe$_2$As$_2$ at 0 (black squares) and 5 (red circles) Tesla.
According to Eq. (2) and (3), both the magnitudes of voltages from the thermocouple and the piezobender, ∆V_T and ∆V_L, should be proportional to the square of the magnitude of the heating voltage V_{sin}. As shown in Fig. 2(c) and 2(d), respectively. At large voltages, ∆V_T becomes lower than the value from linear extrapolation. This is most likely due to the DC heating effect [29], which results in an increase of the specific heat and decrease of ∆T. To avoid this effect, V_{sin} is fixed as 0.4 V in the following measurements.

The frequency dependence of the ∆V_L and ∆V_T can be well described by Eq. 1 with the term 2K/3K neglected, as shown in Fig. 2(a) and 2(b), respectively. At low temperatures (2 and 4 K), f ∆V_T becomes frequency-independent at high frequencies, which is because τ_2 is very small (∼2.3 ms). With increasing temperatures, τ_2 becomes larger so that its effect moves to lower frequencies and there is no frequency-independent region. For f ∆V_L, the frequency-independent region exists at all temperatures (τ_2 is actually set to zero in all fittings). The frequency-independent region means that the signal has the form in Eq. 2. Figure 3 shows the temperature dependence of ∆T, which is calculated by ∆V_T/S with S as the Seebeck coefficient of the thermocouple. It increases with decreasing temperature and shows a dip at T_c, which is consistent with the temperature dependence of the specific heat. Assuming that the specific heat jump at T_c calculated based on 1/∆T is the same as that measured in Fig. 1(d), the calculated specific heat just above T_c is about 10 times larger than the actual value, which suggests that just about 10% of the heating power is applied on the sample. Nevertheless, the oscillating temperature of the sample can still be represented by ∆T.

Figure 3(b) shows the temperature dependence of ∆V_L, which shows a very sharp dip at T_c for all frequencies. This is because the linear thermal expansion coefficient α along the a axis changes sign at T_c [30]. As shown in Fig. 3(c), the phase θ for ∆V_L changes exactly 180 degrees at T_c, which demonstrates the sign change of ∆L across T_c. Figure 3(d) shows the temperature dependence ∆L = k ∆V_L at different frequencies. Interestingly, its temperature dependence is very similar to that of the linear Grünisen parameter Γ_a, which is because Γ_a = α_a/C_a ∝ ∆L according to Eq. 1 and 3.

Figure 3(e) shows the linear thermal expansion α_a along the a axis obtained by Eq. (3) with η = 1. The values of α_a are two orders smaller than those measured by the capacitive dilatometer [30], which means that η is in the order of 10^{-2}. This extremely small value of η makes it hard to calculate the absolute value of the thermal expansion. The temperature dependence of α_a below 5 K

---

**FIG. 2.** (a) & (b) The V_{sin}^2 dependence of ∆V_T and ∆V_L, respectively. The frequency is fixed at 5 Hz. The temperatures are 10 and 1.8 K. The dashed lines are fitted by a linear function for V_{sin} < 0.5 V. (c) and (d) The frequency dependence of f ∆V_T and f ∆V_L, respectively. The solid lines are the fitted results according to Eq. 1.

**FIG. 3.** (a) Temperature dependence of ∆T at 0 T. (b) - (d) Temperature dependence of ∆V_L, θ and calculated ∆L, respectively. The solid line in (d) is Γ_a calculated by α from Ref. 30 and the specific heat of KFe_2As_2. (e) The temperature dependence of the linear thermal temperature expansion along the a axis α_a. The solid line is α_a from Ref. 30, whose values have been divided by 140 to compare with our results. (f) The field dependence of ∆V_L at 3 Hz and 1.8 K for two KFe_2As_2 samples. The angle between the field H and c axis is φ.
shows almost no frequency dependence and can be nicely
normalized to the reported values. With increasing tem-
perature, $\alpha_0$ becomes different for different frequencies,
which is because $\Delta V_T$ becomes frequency dependent as
shown in Fig. 2(c).

In the end, we briefly provide an example to measure
the sample under magnetic field. Figure 3(f) shows the
field-dependence of $V_L$ for two KFe$_2$As$_2$ samples at 1.8
K with the angles between the field and the c-axis as $\phi$
$= 0$ and 6 degrees. While it is not within the scope of
this paper to discuss the physics underlying this data,
the difference between the two sets of data clearly comes
from the vortex dynamics for a layered superconductor
[32][33]. It is clear that our device is also able to measure
the field dependence of the thermal expansion.

IV. DISCUSSIONS

The above results demonstrate that it is possible to
measure the thermal expansion at low temperatures by
the AC method based on a piezobender device. There are
several advantages compared to the capacitive dilatome-
ter. First, the design and fabrication of the sample
holder, and the experimental setup are very simple and
low-cost. The capacitive low-temperature dilatometer on
the other hand is very specialized and its measurement
needs costly high-resolution capacitance meter. Second,
the device here can measure single crystals with thick-
ness of just a few microns, which may be crucial for some
systems where only thin slices of crystals are available.
Third, the resolution is good as shown in Fig. 3(e) and
(f). It is not suitable to directly compare the resolutions
between our device and the capacitive dilatometers since
$\alpha$ is directly obtained as the definition, i.e. $\Delta L/L\Delta T$,
while the latter measure the change of the total length
with the temperature first and then make the differential.
In our case, better resolutions can be achieved in the future by introducing large-gain preamplifier,
better shielding and design of the electrical circuits, and different choices of the heater, the piezobender and the
thermometer. At last, although not achieved by this work, it is possible to also obtain the specific heat by our device
according to Eq. 2. The simultaneous measurements of
the linear thermal expansion $\alpha$ and the specific heat $C$
of a sample means that one can obtain the linear Grüneisen
parameter $\Gamma \propto \alpha/C$. In fact, even without the knowledge
of the specific heat, it is still possible to directly obtain $\Gamma$
as shown in Fig. 3(d) because of the intrinsic correlations
between these physical properties as described by Eq. 1
and 3

However, there are several disadvantages for the TMD
device here. First, it is hard to obtain the absolute
value of $\alpha$. As show above, the values measured here
are more than two orders smaller than the actual ones.
If a sample-independent normalization factor can be ob-
tained by carefully comparing the results between the
TMD and capacitive dilatometers, it may be possible to
calculate the absolute values of $\alpha$. Second, the device
works well below 5 K where the optimal working condition
described by Eq. 2 is satisfied. At higher temperatures,
the effect of $\tau_2$ in $\Delta T$ becomes significant, which
results in the deviation of $\alpha_0$ from the linear temperature
dependence (Fig. 3(e)). It is interesting to note that for
$\Delta V_L$, there is always a region that satisfy the optimal
working condition as shown in Fig. 2(d). It follows that
the $\tau_2$ of the sample, i.e., the time which the sample
attains thermal equilibrium, is much smaller than that of
the thermocouple. If a thermometer with smaller heat
capacity and better thermal conductance can be used,
this issue may be solved.

Despite the above disadvantages, the TMD introduced
here can be used to study some important physical prop-
erties, such as the phase transitions and vortex dynamics
in the superconducting state as shown above. Especially,
since the device works well below 5 K, it may be possible
to apply it below 1.8 K to study quantum phase transi-
tions. Moreover, although it is hard to obtain the abso-
lute value, studying the systematic change of the thermal
expansion in a particular system with doping and mag-
netic field etc is still reliable.

V. CONCLUSIONS

We have designed a temperature-modulated dilatome-
ter based on a piezobender device, which can measure
the linear thermal expansion coefficient and Grüneisen
parameter. Although it is hard to obtain the absolute
values, the device has the capability of measuring very
thin samples with high resolutions as illustrated by mea-
suring KFe$_2$As$_2$ single crystals. Considering that this
device is still a prototype, much improvements should be
possible in the future.

ACKNOWLEDGMENTS

We thank great helps from Prof. Jing Guo. This
work was supported by the National Key R&D Pro-
gram of China (Grants No. 2017YFA0302903 and No.
2016YFA0300502), the National Natural Science Foun-
dation of China (Grants No. 11874401 and No. 11674406),
the Strategic Priority Research Program(B) of the Chi-
nese Academy of Sciences (Grants No. XDB25000000
and No. XDB07020000, No. XDB28000000).

[1] T. H. K. Barron, J. G. Collins, and G. K. White, “Ther-
mal expansion of solids at low temperatures,” Adv. Phys.
29, 609 (1980).
[2] Guo-meng Zhao, M. B. Hunt, and H. Keller, “Strong oxygen-mass dependence of the thermal-expansion coefficient in the manganites ($La_{1-x}Ca_x)$_{$1-y$}Mn$_x$O$_{3-y}$,” Phys. Rev. Lett. 78, 955–958 (1997).

[3] A. Bianchi, R. Movshovich, N. Oeschler, P. Gegenwart, F. Steglich, J. D. Thompson, P. G. Pagliuso, and J. L. Sarrao, “First-order superconducting phase transition in CeCoIn$_5$,” Phys. Rev. Lett. 89, 137002 (2002).

[4] Gaku Motoyama, Takashi Nishioka, and Noriaki K. Sato, “Phase transition between hidden and antiferromagnetic order in URu$_2$Si$_2$,” Phys. Rev. Lett. 90, 166402 (2003).

[5] J. Hemberger, H.-A. Krug von Nidda, V. Tsurkan, and A. Loidl, “Large magnetostriiction and negative thermal expansion in the frustrated antiferromagnet ZnCr$_2$Se$_4$,” Phys. Rev. Lett. 98, 147203 (2007).

[6] F. Hardy, A. E. Böhmer, D. Aoki, P. Burger, T. Wolf, P. Schweiss, R. Heid, P. Adelmann, Y. X. Yao, G. Kotliar, J. G. Donath, F. Steglich, E. D. Bauer, J. L. Sarrao, and J. C. Cooley, “Versatile and compact capacitive dilatometer,” Rev. Sci. Instrum. 77, 123907 (2006).

[7] R. Küchler, T. Bauer, M. Brando, and F. Steglich, “A compact and miniaturized high resolution capacitance dilatometer for measuring thermal expansion and magnetostriiction,” Rev. Sci. Instrum. 83, 095102 (2012).

[8] Satoshi Abe, Fumishii Sasaki, Takeobu Oomishi, Daiki Inoue, Jun Yoshida, Daisuke Takahashi, Hiroyuki Tsuji, Haruhiko Suzuki, and Koichi Matsumoto, “A compact capacitive dilatometer for thermal expansion and magnetostriiction measurements at millikelvin temperatures,” Cryogenics 52, 452 (2012).

[9] R. Küchler, M. Berben, and P. Gegenwart, “A uniaxial stress capacitive dilatometer for high-resolution thermal expansion and magnetostriiction under multietreme conditions,” Rev. Sci. Instrum. 87, 073903 (2016).

[10] R. Küchler, A. Wörl, P. Gegenwart, M. Berben, B. Bryant, and S. Wiedmann, “The world’s smallest capacitive dilatometer for high-resolution thermal expansion and magnetostriiction in high magnetic fields,” Rev. Sci. Instrum. 88, 083903 (2017).

[11] Kenji Uchino and Leslie E. Cross, “A very high sensitivity dilatometer for the direct measurement of piezoelectric and electrostrictive constants,” Ferroelectrics 27, 35 (1980).

[12] R. Küchler, S. Zinth, and P. Gegenwart, “A uniaxial stress capacitive dilatometer for high-resolution thermal expansion and magnetostriiction under multiextreme conditions,” Rev. Sci. Instrum. 87, 073903 (2016).

[13] Tom H. Johansen, “An AC dilatometer for linear expansivity measurement,” High Temperature High Pressure 19, 77 (1987).

[14] Christofor Meingast, Frederic Hardy, Rolf Heid, Peter Adelmann, Anna Böhmer, Philipp Burger, Doris Ernst, Rainer Fromknecht, Peter Schweiss, and Thomas Wolf, “Thermal expansion and grüneisen parameters of Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$: A thermodynamic quest for quantum criticality,” Phys. Rev. Lett. 108, 177004 (2012).

[15] Y. Tokiwa, E. D. Bauer, and P. Gegenwart, “Zero-field quantum critical point in CeCoIn$_5$,” Phys. Rev. Lett. 111, 107003 (2013).

[16] Alexander Steppke, Robert Küchler, Stefan Lausberg, Edit Lengyel, Lucia Steinke, Robert Borth, Thomas Lühmann, Cornelius Krellner, Michael Nicklas, Christoph Geibel, Frank Steglich, and Manuel Brando, “Ferromagnetic quantum critical point in the heavy-fermion metal YbNi$_2$(P$_{1-x}$As$_x$)$_2$,” Science 339, 933–936 (2013).

[17] G. M. Schniedeshoff, A. W. Lounsbury, D. J. Luna, S. J. Tracy, A. J. Schramm, S. W. Tozer, V. F. Correa, S. T. Hannahts, T. P. Murphy, E. C. Palm, A. H. Lacerda, S. L. Bud’ko, P. C. Canfield, J. L. Smith, J. C. Lashley, and J. C. Cooley, “Towards the identification of a quantum critical line in the ($La_{1-x}Pr_x$)$_2$CuO$_4$,” Phys. Rev. Lett. 83, 085111 (2012).

[18] Daiki Inoue, Daisuke Kaido, Yuta Yoshikawa, Mitsuuyki Minegishi, Koichi Matsumoto, and Satoshi Abe, “Thermal expansion and magnetostriiction measurements with a high sensitive capacitive dilatometer at millikelvin temperatures,” Journal of Physics: Conference Series 568, 032001 (2014).

[19] R. Küchler, C. Stingl, and P. Gegenwart, “A uniaxial stress capacitive dilatometer for high-resolution thermal expansion and magnetostriiction under multietreme conditions,” Rev. Sci. Instrum. 87, 073903 (2016).

[20] Tom H. Johansen, “An AC dilatometer for linear expansivity measurement,” High Temperature High Pressure 19, 77 (1987).

[21] Yanzhong Gu, Zhaoyu Liu, Tao Xie, Wenliang Zhang, Lingxiao Zhao, Lifang Lin, Zhiang Xu, Guotai Tan, Genfu Chen, Ziyi Meng, Yi-feng Yang, Huiqian Luo, and Shiliang Li, “A thermodynamic quest for quantum criticality,” Phys. Rev. Lett. 108, 177004 (2012).

[22] Yanzhong Gu, Zhaoyu Liu, Tao Xie, Wenliang Zhang, Dongliang Gong, Xiaoyan Ma, Xianggang Qiu, Pengcheng Dai, Yi-feng Yang, Huiqian Luo, and Shiliang Li, “Unified phase diagram for iron-based superconductors,” Phys. Rev. Lett. 117, 157002 (2016).

[23] Y. Tokiwa, E. D. Bauer, and P. Gegenwart, “Zero-field quantum critical point in CeCoIn$_5$,” Phys. Rev. Lett. 111, 107003 (2013).

[24] R. Küchler, S. Zinth, and P. Gegenwart, “A uniaxial stress capacitive dilatometer for high-resolution thermal expansion and magnetostriiction under multietreme conditions,” Rev. Sci. Instrum. 87, 073903 (2016).

[25] Tom H. Johansen, “An AC dilatometer for linear expansivity measurement,” High Temperature High Pressure 19, 77 (1987).

[26] Zhuqiang Liu, Yanzhong Gu, Wei Zhang, Dongliang Gong, Wenliang Zhang, Tiao Xie, Xinya Lu, Xiaoyan Ma, Xizhian Zhang, Rui Zhang, Jun Zhu, Cong Ren, Lei Shan, Xianggang Qiu, Pengcheng Dai, Yi-feng Yang, Huiqian Luo, and Shiliang Li, “A thermodynamic quest for quantum criticality,” Phys. Rev. Lett. 108, 177004 (2012).

[27] Yanzhong Gu, Zhaoyu Liu, Tao Xie, Wenliang Zhang, Dongliang Gong, Ding Hu, Xiaoyan Ma, Chunhong Li, Lingxiao Zhao, Lifang Lin, Zhiang Xu, Guotai Tan, Genfu Chen, Ziyi Meng, Yi-feng Yang, Huiqian Luo, and Shiliang Li, “Unified phase diagram for iron-based superconductors,” Phys. Rev. Lett. 117, 157002 (2016).

[28] Paul F. Sullivan and G. Seidel, “Steady-state, ac-temperature calorimetry,” Phys. Rev. 173, 679–685 (1968).
[29] Eberhard Gmelin, “Classical temperature-modulated calorimetry: A review,” Thermochim. Acta 304–305, 1 (1997).

[30] X. Ma and S. Li, Unpublished.

[31] Zhaoyu Liu, Yanhong Gu, Wenshan Hong, Tao Xie, Dongliang Gong, Xiaoyan Ma, Jing Liu, Cheng Hu, Lin Zhao, Xingjiang Zhou, R. M. Fernandes, Yi-feng Yang, Huiqian Luo, and Shiliang Li, “Nonlinear uniaxial pressure dependence of $T_c$ in iron-based superconductors,” Phys. Rev. Research 1, 033154 (2019).

[32] G. Blatter, M. V. Feigel’man, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, “Vortices in high-temperature superconductors,” Rev. Mod. Phys. 66, 1125–1388 (1994).

[33] A. Grigorenko, S. Bending, T. Tamegai, S. Ooi, and M. Henini, “A one-dimensional chain state of vortex matter,” (2001).