Analysis of peak effect in the critical current density and flux pinning properties in iron based superconducting Ca$_{10}$(Pt$_4$As$_8$)(Fe$_{2-x}$Pt$_x$As$_2$)$_5$ single crystal

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We present the magnetic properties of the iron based superconducting Ca$_{10}$(Pt$_4$As$_8$)(Fe$_{2-x}$Pt$_x$As$_2$)$_5$ ($x=0.01$) single crystal as a function of field and time. The single crystals were grown by Bridgman method and showed $T_c$ of 32 K. The results show that the well-known secondary peak effect becomes prominent in certain temperature range in the field dependent magnetic hysteresis. Moreover, the maximum of pinning force density $F_{p,max}$ versus $H_{max}$ follows a scaling law $F_{p,max} \approx 49.5H_{max}^{3/2}$ indicating the single type pinning mechanism is involved in the sample within our measured temperature range. The time dependence of the magnetization indicates thermally activated flux motion and the relaxation rate reveals a plateau in the temperature region where secondary peak effect is more prominent after that a sudden increase is observed. We found that the magnetization dependence of activation energy $U$ obtained by Maley’s method follows a power law in low temperature region with exponent $\mu = 0.15$ which is in good agreement with collective pinning theory.

1. Introduction:
The enigmatic characteristics of superconductivity have a special attraction for the condensed matter physicists. After the discovery of first iron based superconductor [1], a variety of superconducting materials have been reported. Moreover, all of the iron based superconducting materials consist of edge-sharing FeAs$_4$ and FeSe$_4$ tetrahedra along with spacer layers [1,2]. Recently, two new superconducting compounds with composition Ca$_{10}$(Pt$_3$As$_8$)(Fe$_{2-x}$Pt$_x$As$_2$)$_5$ (10-3-8) and Ca$_{10}$(Pt$_4$As$_8$)(Fe$_{2-x}$Pt$_x$As$_2$)$_5$ (10-4-8) were discovered [3]. The crystal structure of 10-3-8 compound is a triclinic crystal with space group P-1, whereas 10-4-8 is of higher symmetry tetragonal crystal structure, respectively [3]. The doping behavior of the CaPtFeAs system is similar to that of FeAs systems in which the electron doping outside the FeAs layer significantly enhances the $T_c$ [3].

The critical current density extracted from field dependence magnetic hysteresis gives important information about the vortex matter in a superconductor. The secondary peak effect is a unique feature in the field dependence of magnetic hysteresis in high $T_c$ superconductor. Several reasons have been presented to explain the secondary peak effect at specific temperature and applied magnetic field.

In this work, we analyze the flux pinning properties of Ca$_{10}$(Pt$_4$As$_8$)(Fe$_{2-x}$Pt$_x$As$_2$)$_5$ with $x = 0.01$ as a function of applied magnetic field and time. The variation of the critical current density $J_c$ with respect to applied field and temperature is discussed. Moreover, the time dependence of the magnetization is analyzed in the temperature region where prominent secondary peak effect is observed. The differences of the observed behavior with that of other high $T_c$ superconductors are discussed.
2. Experimental Details:
The Ca$_{10}$(Pt$_4$As$_8$)(Fe$_{2-x}$Pt$_x$As$_2$)$_5$ with $x = 0.01$ was grown by Bridgman method [4]. FeAs precursor, Pt wire and Ca pieces were mixed together according to stoichiometric ratio and put into alumina crucible. The alumina crucible was then put into molybdenum crucible and sealed using arc welding system. Mixing and sealing steps were performed in under argon atmosphere. Single crystal was grown at 1550°C for around 170 hours with slow moving down. Single crystals of maximum cm size were found upon crucible breaking. The structural characterization of the sample was performed using X-ray diffractrometry (XRD) with Cu Kα radiation source. The compositional analysis was performed using an energy dispersive X-ray analysis (EDAX) with scanning electron microscopy (SEM). The field dependence of magnetic hysteresis and magnetic relaxation measurements were carried out with superconducting quantum interference device (SQUID) magnetometer in the case when $H||c$.

3. Results and Discussion:
The temperature dependence of magnetic susceptibility was measured at 10 Oe. The onset transition temperature $T_{c,onset}$ is about 32 K. A sharp transition indicates the existence of single superconducting phase. At low temperatures, the zero field cooled susceptibility is about $4 \pi \chi = -0.9$, which corresponds to almost complete screening of single crystal interior. The field cooled susceptibility is $4 \pi \chi = -0.05$ indicating the strong flux pinning at low fields in our single crystal. Fig. 1 presents the field dependence of the magnetic hysteresis in Ca$_{10}$(Pt$_4$As$_8$)(Fe$_{2-x}$Pt$_x$As$_2$)$_5$ ($x = 0.01$) at several temperatures. Moreover, the magnetic hysteresis curves in our measured temperatures are symmetric. A well-formed secondary peak can also be seen in the specific temperature range which is a characteristic of some of the high $T_c$ superconductors. Recently, the secondary peak was also observed in some iron based superconductors, e.g., (Ba,K)Fe$_2$As$_2$, Ba(Fe,Co)$_2$As$_2$, and Ba(Fe,Ni)$_2$As$_2$ superconductors [5,6]. For instance, in Co-doped Ba-122 system, the secondary peak was interpreted as a crossover from one kind of vortex dynamics to other.

The critical current density $J_c$ in our sample was calculated using Bean Model [7] as $20 \Delta M/[a(1-a/3b)]^{-1}$, where $\Delta M$ is the width of magnetic hysteresis, $a$ and $b$ is the sample dimensions in cm with $a < b$ and $J_c$ is in A/cm$^2$. The critical current density was estimated about $5 \times 10^4$A/cm$^2$ at 5 K and remains field independent up to 5 T. Fig. 2 displays the pinning force density ($F_p=J_cB$) as a function of the applied field for our Ca$_{10}$(Pt$_4$As$_8$)(Fe$_{2-x}$Pt$_x$As$_2$)$_5$ sample. With the increase of temperature, the maximum of $F_p$ is shifted to lower applied field as shown in Fig. 2. Moreover, the inset of Fig. 2 exhibits the maximum of pinning force density $F_{p,max}$ as a function of corresponding field $H_{max}$. The solid line in the inset is a fit to $F_{p,max} = 49.5H_{max}^{3/2}$ which is in good agreement with the experimental data. Therefore, this scaling of $F_{p,max}$ indicates that a single type of pinning mechanism is involved in our sample within measured temperature range in agreement with the previous reports [5,6].

![Fig. 1. Field dependence of the magnetization in increasing and decreasing fields in temperature range from 11 to 23 K for $H||c$.](image1)

![Fig. 2. Field dependence of $F_p$ for temperatures from 11 to 19 K. Inset: $F_{p,max}$ as a function of $H_{max}$. The solid line is a fit of $F_{p,max} = 49.5H_{max}^{3/2}$.](image2)
Figure 3 shows a typical time dependence of magnetization at various temperatures in the applied field of 1 T in \( \text{Ca}_{10}(\text{Pt}_{4}\text{As}_{8})(\text{Fe}_{2-x}\text{Pt}_{x}\text{As}_{2})_5 \) \((x = 0.01)\) single crystal. Moreover, the logarithmic dependence of \( M \) vs \( t \) in Fig. 3 is the same as expected in the model of thermally activated flux motion.

Fig. 4 shows the relaxation rate \( S = |d \ln M / dt| \) obtained at 1 T as a function of temperature for our sample. Moreover, the high relaxation rate in our sample is in similar range reported previously for YBCO [8]. In addition, we can see a plateau in the intermediate temperature range. This plateau in the particular temperature range cannot be explained within the single vortex creep theory with the rigid hopping length predicted by Anderson-Kim model. Recently, similar behavior was observed in \( \text{Ba}(\text{Fe}_{0.925}\text{Co}_{0.075})_2\text{As}_2 \) and \( \text{FeTe}_{0.6}\text{Se}_{0.4} \) superconductors and was attributed to the vortex collective pinning [9,10]. However, our result for vortex creep rate is in contrast to the case for \( \text{MgB}_2 \) superconductor in which the relaxation rate increases linearly with temperature which indicates a thermally activated hopping of vortices with rigid length [11].

The critical current \( J_c \) dependence of the activation energy \( U \) is an important parameter for investigating the vortex dynamics in the sample. For instance, a well-known equation for determining the activation energy \( U \) was proposed by Maley et al using the relaxation rate \( S \) as \( dM/dt \propto \exp(-U/kT) \) calculated in the irreversible region [12]. The activation energy is then finally calculated as \( U = k_B T (A - \ln|dM/dt|) \), where \( A \) is the time independent constant corresponded to the average hopping velocity. Fig. 5 shows the dependence of the activation energy on the magnetization at temperatures from 10 to 20 K. Moreover, up to 14 K, all the curves are scaled together but we were unable in scaling the activation energy above 14 K. The Maley’s method is only valid at low temperature \( (T<T_c/3) \) where the temperature dependence of the activation energy \( U(T) \) is relatively weak. We selected the temperature range in which the secondary peak is prominent which is slightly above \( T<T_c/3 \) and therefore found an excellent agreement with the temperature range where Maley’s method is applicable. Furthermore, a sudden increase of the relaxation rate above 17 K is due to a crossover between different vortex creep regions as shown in Fig. 4 supporting our results in Fig. 5. For analyzing the experimental data points of the activation energy at various temperature, we used the power law from the collective creep theory [13] which is given as \( U \propto \left( J_c / J \right)^\mu - 1 \), where \( J_c \) is the critical current density and \( \mu \) is a critical exponent describing the nature of the pinning barrier. From the fitting we get \( \mu = 0.15 \) for our temperature range which is in agreement with collective pinning theory and thus confirms the flux creep as a result of the motion of individual vortices [16]. Furthermore, according to collective pinning theory the value of \( \mu \) will be significantly increased at higher temperatures suggesting a crossover from the single vortex to vortex-bundle pinning state. Therefore, from our results we can conclude that a crossover between different pinning regimes occurs at around 17 K.
Conclusion:
The superconducting \( \text{Ca}_{10}(\text{Pt}_4\text{As}_8)(\text{Fe}_{2-x}\text{Pt}_x\text{As}_2)_5 \) (\( x=0.01 \)) single crystals were grown by Bridgman method. The transition temperature \( T_c \) was found at 32 K measured by temperature dependence of magnetization. The field and time dependence of the magnetization was measured in various fields and temperatures. We found a prominent secondary peak effect in the magnetic hysteresis in particular temperature range in agreement with other high \( T_c \) superconductors. A scaling law was followed by \( F_{\text{max}} \) vs \( H_{\text{max}} \) indicative of a single type of pinning activated in the sample at least in our measured temperature range. The activation energy \( U(J) \) calculated by Maley’s method have shown a trend in the favor of the collective pinning model by following a power law.

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References:
[1] Kamihara Y, Watanabe, Hirano T M, and Hosono H, (2008) \textit{J Am Chem Soc}. 130 3296.
[2] Hsu F C et. al, (2007) \textit{Proc Natl Acad Sci}. 105, 14262.
[3] Kakiya S, Kudo K, Nishikubo Y, Oku K, Nishibri E, Sawa H, Yamamoto T, Nozaka T, and Nohara M, (2011) \textit{J. Phys. Soc. Jpn}. 80, 093704.
[4] Song Y J, Ghim J S, Min B H, Kwon Y S, Jung M H and Rhyee J S, (2010) \textit{Appl Phys Lett}. 96 212508.
[5] Sun D L, Liu Y, and Lin C T, (2009) \textit{Phys Rev B}. 80 144515.
[6] Yamamoto A et al, (2009) \textit{Appl Phys Lett}. 94 092504.
[7] Bean C P, (1964) \textit{Rev. Mod. Phys.}, 36 31.
[8] Blatter G et al, (1994) \textit{Rev Mod Phys} 66 1125.
[9] Haberkorn N, Maiorov B, Usos I O, Weigand M, Hirata W, Miyasaka S, Tajima S, Chikumoto N, Tanabe K, and Leonardo Civale, (2012) \textit{Phys Rev B} 85 014522.
[10] Sun Y, Taen T, Tsuchiya Y, Pyon Y S, Shi Z, and Tamegai T, (2013) \textit{EPL}, 103 (2013) 57013.
[11] Malozemoff A P and Fisher M P A, (1990) \textit{Phys Rev B}. 42 6784 (R).
[12] Maley M P, Willis J O, H. Lessure H, and McHenry M E, (1990) \textit{Phys Rev B}. 42 2639.
[13] Anderson P W, and Kim Y B, (1964) \textit{Rev Mod Phys} 36, 39.