اطوارالدوامية الجديدة والتلاعب الدوامية في الموصلات الفائقة ذات خواص عالية التباين

بواسطة مستشعرهول الماسح مايكروسكوبي

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☐ **الملخص**

تم استخدام المسح المجهر المايكروسكوبي لتفسير التفاعلات الحاصلة بين دوامات المجال المغناطيسي المسمى جوزسفسون و عند اعلى المجالات الداخلة في كل تقاطع للبنية اللبلورية وبنكيك للمركب(2212) $Bi_2Sr_2CaCu_2O_{8+\delta}$ لمادة الفائق التوصيل

استخدمت جهازمسح المجهر المايكروسكوبي لدراسة هيكلية الدوامة عند نقاط التقاطع النظام البنية اللبلورية تحت تاثير مجال المغناطيسي الخارجي. وهذه التفاعلات بين هذا نوعين من الدوامتين تعتمد على مقدار حجم التقاطع الحاصل بينهما وكذلك على درجة الحرارة وايضا تعتمد على الفجوة والمساحة بين سلاسل التي يتغير عكسيا مع مجال المغناطيسي الداخل. سلاسل الدوامات تظهر بوضوح عند اعلى مجال مغناطيسي داخل وبحدود ٣١٥ كاوس اما المجال الخارج تكون تتراوح ما بين ٦,٨-١,٧ كاوس عند ٨٥ كلفن . واخيرا, دراسة هذه السلاسل تسمح لفهم أفضل للنظام تقاطع الدوامتين لمادة الفائق التوصيل.

Novel vortex phases and vortex manipulation in highly anisotropic superconductors by Scanning Hall Probe Microscopy (SHPM)

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ABSTRACT

Scanning Hall probe microscopy (SHPM) has been used to demonstrate the interaction of pancake vortices with the Josephson vortex lattice in $Bi_2Sr_2CaCu_2O_{8+\delta}$ *(2212)* single crystals at large in-plane fields in the ''crossing lattices'' regime of highly anisotropic cuprate superconductors. SHPM has been used to study vortex structures in the interacting crossing lattices regime under applied in and out-of- plane magnetic fields. The interactions between the pancake and Josephson vortices (JV) depend on the values of crossing fields and temperature and the space between chains varies inversely with the in-plane field. These chains are clearly visible at very high in-plane fields $H_{II} \sim 315$ G over a range of out-

of-plane fields 1.7- 6.8 G at 85 K. The study of such chains allows a better understand the regime of crossing vortex lattices in highly anisotropic cuprate superconductors.

KEYWORDS: 2DEG Hall-probe sensor, GaAs/AlGaAs heterostructures ,scanning Hall probe microscopy technique.

1. INTRODUCTION

Vortex structure in anisotropic layered superconductors such as the $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) compounds have been extensively investigated in recent years displaying a rich phase diagram depends on the direction and strength of the magnetic field. When the external applied magnetic field is inclined away from the C-axis (cuprate planes), the different components of magnetic flux generate two different types of magnetic vortices: pancake vortices (PVs) confining in the superconducting planes are responsible for the perpendicular flux component and Josephson vortices (JVs) located between the superconducting planes current the in-plane flux [1].

The crossing lattice "combined lattice" of Abrikosov vortices (AVs) and Josephson vortices (JVs) exist in strongly anisotropic layered superconductors, in a tilted magnetic field, due to the interaction between The line of PVs "Abrikosov vortices" with JVs. Thus, the perpendicular line of PVs vortex is attracted and distorted by JVs, so that the JV stacks accumulate alongside PVs, formatting a vortex row with enhanced

density. Lately, the scanning Hall probe microscopy have been used to study the vortex chains in BSCCO were performed and displayed the stability of the dense vortex chain state even in the absence of a lattice and in a very weak perpendicular magnetic field . Also chains of higher vortex density were observed in Bitter decorations, and magneto-optical imaging, and explained as crossing lattices of pancake and Josephson vortices. In the present work, the High resolution scanning Hall probe microscopy have been used to search for novel phases of vortex matter in single crystals of the high temperature superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ and investigate the evolution of a coupled JV-PV in highly anisotropic $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals depending on temperature and applied field [2, 3].

2. Experimental procedure

2.1 Hall-probe fabrication for 2DEG sensor

The 2DEG Hall-probe fabrication on GaAs/AlGaAs heterostructures process looks like Bi-Hall probe fabrication with a few differences such as coarse etching, Hall sensor etch, tip deposition(STM) , deep etch and cleave it for four parts.

A GaAs/AlGaAs heterostructure is cleaved into 6 mm $\times$ 6 mm square chips and cleaned in the usual way as mentioned previously but using ultrasonic at 25% power. In order to obtain high quality Ohmic contact and remove oxide, the surface should be dipped in a solution $HCl:H_2O$

with ratio 1:1 for 30 seconds and rinsed them in DI water for 10 seconds. Once the oxide is removed, the samples are mounted in a thermal evaporator. In that case, these following materials for instance 66 nm Ge, 134 nm Au, 20 nm Ti and 200 nm Au are evaporated in the same operation and the vacuum chamber has 2.4×10^{-6} mbar to form high quality Ohmic layers. These final two layers provide a contact surface for ultrasonic bonding i.e.Ti helps Au stick to the surface, and this last layer serves for easy bonding of the sensor the chip holder. Finally, the chips are annealed under a mix of gas 95 % N_2 and 5% H_2 at 430 ^{0} C for 2 minutes so that they can form good contact with 2DEG (see figure 1(a)). The regions between Ohmic contact leads are removed by using wet coarse etching using the usual lift-off way with the exception that the speed of spinning is 5000 rmp for 30 seconds and surface oxides are removed by dipping the samples in HCl:H_2O with ratio 1:1 solution for 30 seconds and then washing them by DI H_2O for 10 seconds and drying them. After that, the chips are dipped immediately in (H_2SO_4:H_2O_2:H_2O) (1:8:160) solution to etch the chips, which gives an etch rate of ~ 0.26 $\mu m \ min^{-1}$(see figure 1 (b)).
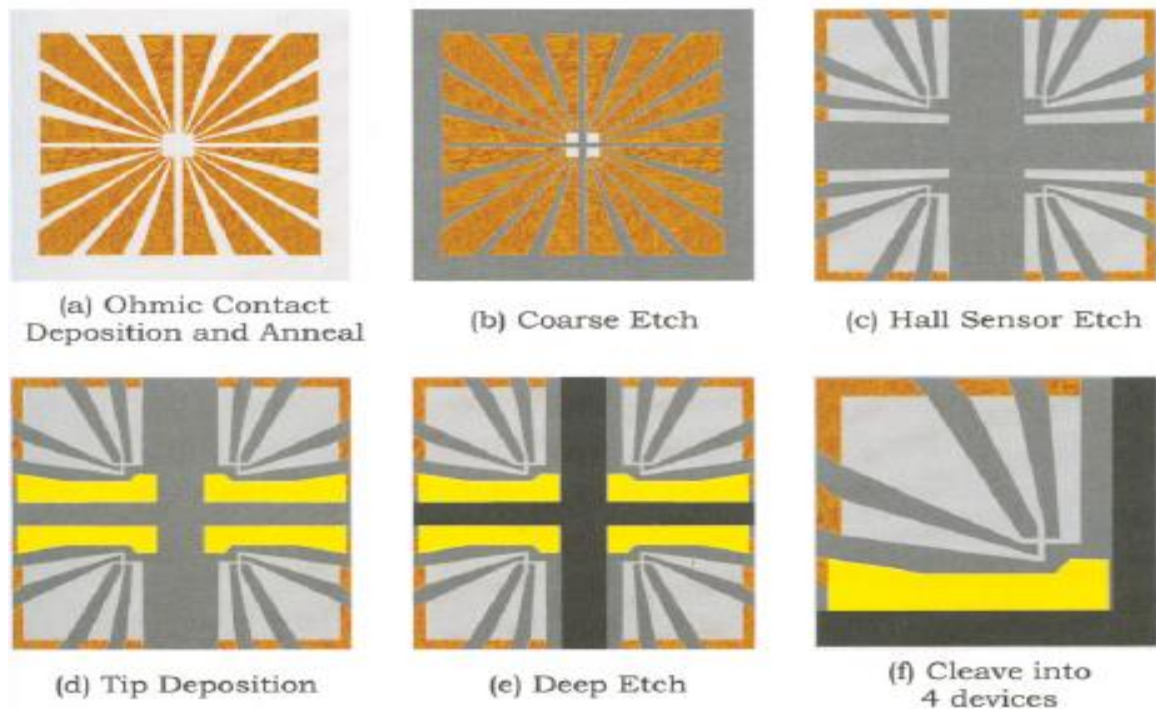
Figure. (1): **The fabrication steps of GaAs/AlGaAs heterostructures Hall sensor** [4].

In is noted that, either the Hall-Probe etch is complicated by the e-beam resist orthe slow etch solution (H_2SO_4:H_2O_2:H_2O) with the ratio (1: 8: 1000) with etch rate~ 0.04 μm /min is used to control the etching process. The etching process by solution for a Hall probe is very gentle and for one minute. If the resistances between Ohmic contacts were very low, the process was repeated for 30 seconds. This process was repeated until the resistance of Hall probe leads became around ten KΩ (see figure 1(c)). The last step is tip metallization. The process part is just the same as the Ohmic contact process except a tip mask is used in this process

which is coated with10 nm layer of Ti and 50nm layer of gold respectively without annealing (see figure 1(d)). This metallization aims the high conductivity along the tip and easy approach to the sample before scanning process. The STM tip is an important point of the corner of the chip, a deep etch is performed in the same way as a coarse etching except the ratio of the etching solution is (H_2SO_4: H_2O_2: H_2O) (1: 8: 80) with the rate of etching 540 nm min^{-1}. The final stage after the deep etch is to cleave the sample into four devices using a diamond scribe (see figure 1 (e) and (f)).

To ensure there is no open circuit or short regions between leads in low temperature at 77K,the resistances of the Hall sensors are measured using a resistance probing station (see figure 2) [4].
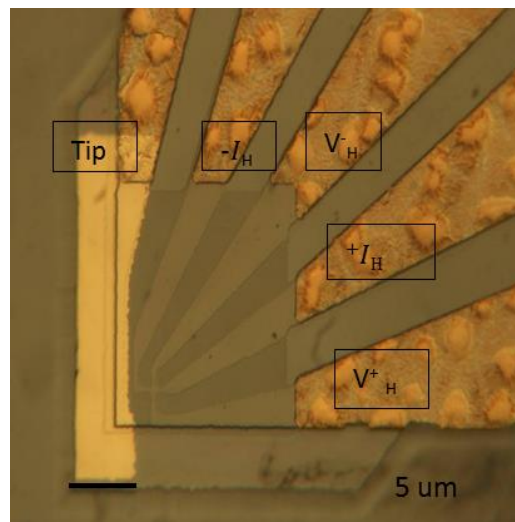

Figure. (2): **The gold coated tip is shown near the Hall-Probe**.

The Hall sensor is mounted on a chips carrier using Oxford Instruments low temperature epoxy, and then the Ohmic contact leads are bonded with the chip carrier by 25 μm diameter gold wires using an ultrasonic wire bonder. Finally, the chips carrier is mounted on an SHPM head (see figure 3).
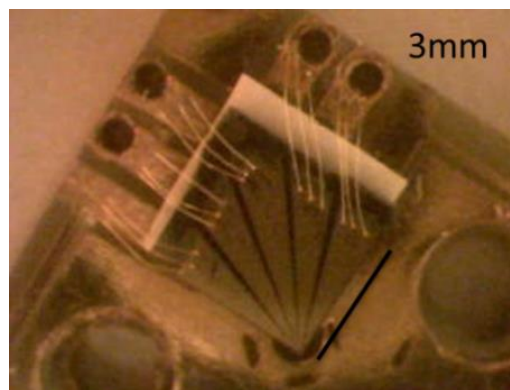

Figure. (3)**: Diced and packaged Hall-Probe with 3mm scale bar.**

Before mounting the sample BSCCO (2212) on a sampler holder, the sample BSCCO (2212) is coated with a conductive surface like gold so that, the tunnel current can be presented between the tip of the Hall probe and the conducting surface of the sample BSCCO (2212). Then the sample BSCCO (2212) is glued onto the sample holder on XY slider with silver conductive paint and left to dry for one hour. Additionally, the sample puck is mounted on SHPM Head, then the angle is adjusted between sample BSCCO (2212) and Hall probe around 1-2 degrees. If the angle between the sample BSCCO and the Hall-Probe sensor is not correct, the Hall-Probe sensor will crash into the sample BSCCO surface

and damage both the Hall-Probe sensor and the sample BSCCO. Finally, a gap should be left between the quartz tube and the sample BSCCO around 250 µm. The sensors is then attached to the piezoelectric scanner tube of the SHPM. (See figure 4).
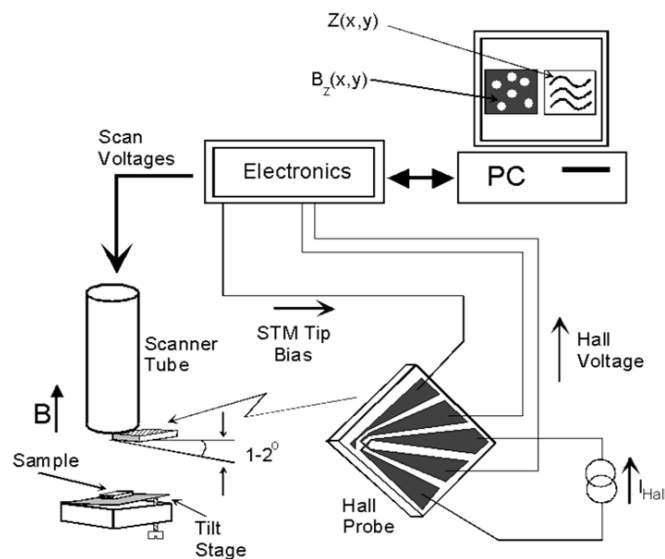

Figure. (4): **Schematic diagram of a scanning Hall probe microscope** [5].

As a result, a coarse approach mechanism is started; after the system has cooled down to 77K. The Hall probe is mounted onto the piezoelectric scanner tube of a commercial low temperature STM system. The Hall sensor and sample holder assembly are referred to as the 'head' of the

SHPM. The scanning tunneling microscope is an instrument in which a sharp conducting tip, attached to the piezoelectric drive (using stick slip principle), is brought close enough to a surface of sample BSCCO (2212). So that, the electrons can tunnel between them. When the bias voltage (V) is applied between the wire and the surface, there will be a current known as a tunneling current (I). If the tip is to touch the surface of BSCCO a current would flow, conversely if the tip is far away from the surface of BSCCO no current will flow. Therefore, a STM technique is very sensitive. A sample is the material to be studied or under investigation. STM being a surface sensitive probe, sample preparation is crucial. There are two important components of a good sample: The sample surface must be kept ultra clean and it should be flat. In addition, the corners of the sample (2212) are checked by the Hall-Probe and the sample is scanned. The scanner piezo in this STM is a tube which is electronically divided into four sections outside which are responsible for (x y) motion and an undivided part inside which takes care of the (z) motion as previously mentioned [6].

3. RESULTS AND DISCUSSION

3.1 Vortex chain spacing as a function of in-plane field

The relationship between the applied in-plane magnetic field H_{II} and separation of vortex chains at 85K in regime of highly anisotropic cuprate superconductors $Bi_2Sr_2CaCu_2O_{8+\delta}$ (2212) single crystals using Scanning

Hall probe microscopy (SHPM) was studied. The fields parallel and perpendicular to the sample plane were produced by two separate sets of coils which allowed one to vary the field components. It was observed that the distances between chains decreases with increase in (H_{II}) and the density of chains increases until they do start to interact strongly. Figure 5 presents a set of images for $Bi_2Sr_2CaCu_2O_{8+\delta}$ (2212) single crystals which are observed in an increasing in-plane field. The images show black lines that shrink with decrease crease of chains number after application of a small normal field $H_{II} = 73.5$ G in the presence of the in-plane field. They are manifestation of Josephson vortex stacks decorated by pancake vortices. In small in-plane fields the decorated Josephson vortices are not regularly spaced which is caused by the weak interaction between the distant Josephson vortex stacks. Hence, the equilibrium separation between PV's on a JV stack is controlled only by the in-plane field B_{II}. So, in both- images G and H we find increase the density of chains with increase magnetic field (in-plane field) due to increase number of flux lines which become penetrate depth (λ) bigger than coherence length(ξ).
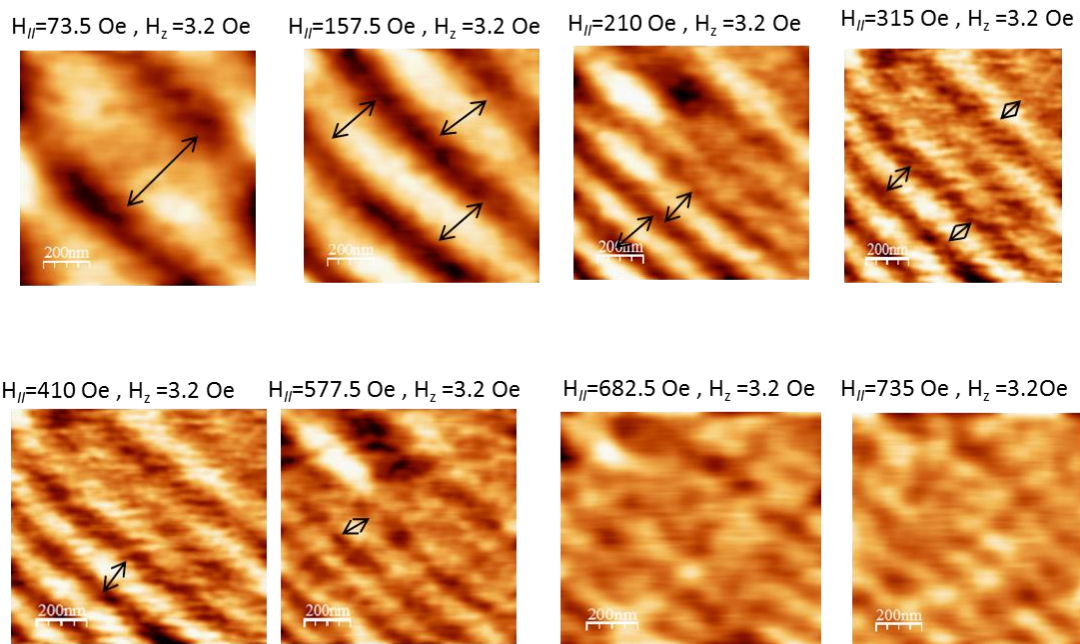
Figure (5): **The distance between chains converge with increase in-plane field at 85K by using (SHPM).**

Figure 6, describes that the distance between chains which are different for every point in graph and it has error bars due to the variation of the spacing between chains. Therefore, we chose this option to obtain best measurements. The number of chain can be concluded and depend on in-plane field and temperature fixed at 85K. When in-plane field applied parallel to the Cu-O planes the vortex cores prefer to locate in the normal spaces between planes. These are called Josephson vortices which currents giving rise to them have to cross the superconductor Cu-O planes by Josephson tunnelling.
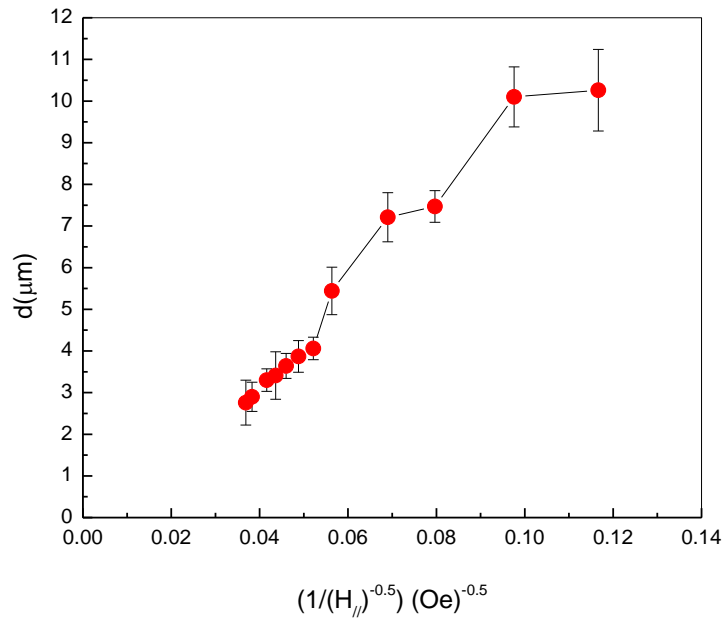
Figure. (6): **The distance between chains decreases with increasing in-plane field at 85K**

3.2 PV structure of vortex chains at very high in-plane fields

The structure of Pancake vortex (PV) at very high in-plane fields (H_{II}) was studied while gradually increasing the out-of-plane field (Hz) at 85K using Scanning Hall probe microscopy (SHPM). In figure 7 shows in-plane field is constant at 315 Oe and the range of out-of-plane field around (0 – 6.8) Oe.
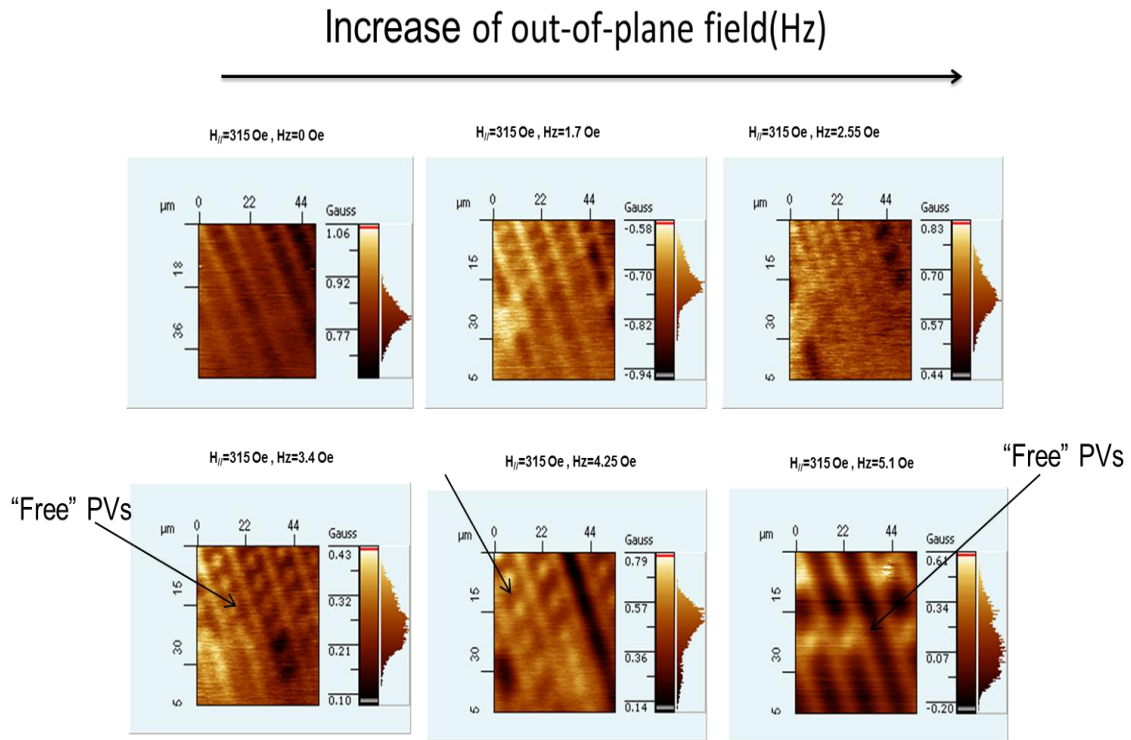
Figure (7): **Stacks of pancake vortices (PVs) and Josephson vortices (JVs) in a Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (2212) single crystal at 85K in which H$_{//}$ =315 G and Bz (0 - 5.1 G).**

The SHPM image shown in figure 7 illustrates what the interacting JV-PV structures actually look like when JV stack spacing's are very small at very high in-plane fields. In general, the trapping of PV stacks by JV traps is dominant over the conventional PV pinning at 85K and the short range repulsion between PVs in the same Cu-O plane. When applied both crossing magnetic fields stacks of JVs with a chain of PVs attracted to

them were observed. The JV chains are close enough together that they interact strongly. In these images there is a row of "free" PVs trapped between each chain of decorated JV stacks especially, with increase out-of-plane field over a broad magnetic field range 0 Oe–6.8 Oe. But, spaces between chains increased from range 3.4 Oe -6.8 Oe and these spaces depend on $1/\sqrt[2]{H//}$ also on the PV density. As a result, we will seek to find new unidentified vortex matter phases at very high in-plane magnetic fields.
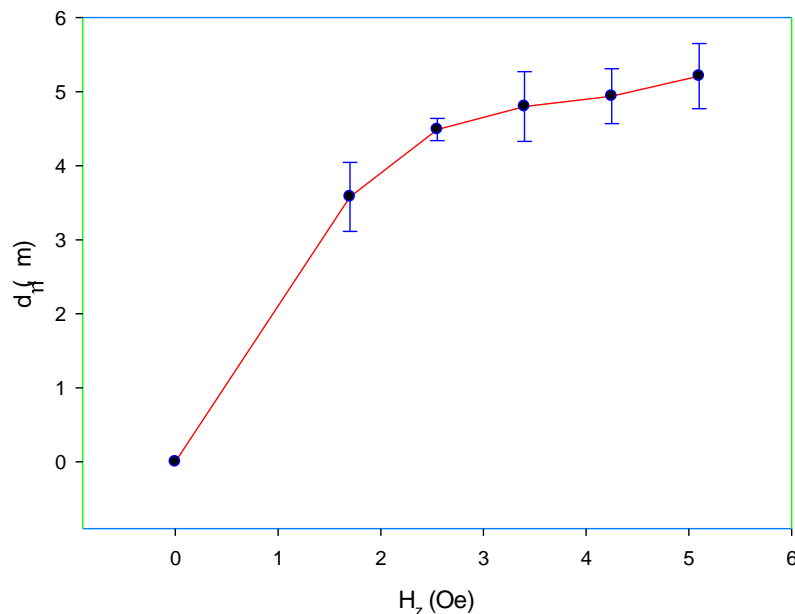

Figure. (8): **The in-plane field (H$_{//}$) was held constant at 315 Oe while the (H$_z$) was varied between 0 – 6.8 Oe**.

The structure of JV stacks 'decorated' with PVs was studied at very high in-plane fields ($H_{//}$) while the out-of-plane field (Hz) was gradually increased at 85K. In the figure 8 shown the in-plane field was held constant at 315 Oe while the out-of-plane field was varied between (0 − 6.8) Oe. The SHPM images illustrate what the interacting JV-PV structures actually look like when JV stack spacing's are very small at very high in-plane fields. At low in-plane field the trapping of PVs by JV stacks dominates over the short range repulsion between PVs on adjacent stacks. However, at very high in-plane fields the JV stacks are close enough together that PVs in adjacent chains start to interact quite strongly. At this point the JV stack spacing becomes dependent on both in-plane and out-of-plane (equivalent to PV density) fields, not just on $1/\sqrt{(H_{//})}$ as is generally assumed.

In these SHPM images there is a row of "free" PVs trapped between each chain of 'decorated' JV stacks. Scanning Hall probe microscopy (SHPM) has been used to demonstrate the interaction of pancake vortices with the Josephson vortex lattice in $Bi_2Sr_2CaCu_2O_{8+\delta}$ *(2212)* single crystals at large in-plane fields in the ''crossing lattices'' regime of highly anisotropic cuprate superconductors. In a mixed state, type II superconductors contain a lattice of small regions of non-superconducting or "normal" material called vortices. Vortices allow the magnetic field to penetrate the sample. This implies, vortices involve one flux quantum and it has core and there are two parameters of vortices such as penetration

depth (λ) and coherence length (ξ). The Ginsburg-Landau parameter (κ) is different for every superconductors of type I and type II because value of these parameters uneven in both types. Vortices are affected by the Lorentz force either the vortices are pinned or motion, as explained in detail at introduction. When a magnetic field B_z applied perpendicular to the superconducting $Cu-O_2$ layers in highly anisotropic BSCCO (2212), a lattice of stacks circular 'pancake' vortices forms and the super current are largely confined to planes of Cu-O atoms which are thinner than the layer spacing. In same layer, Pancake vortices repel each other, while those in different layers attract each other. In contrast, an orthogonal elongated lattice of elliptical Josephson vortices forms when the applied field is parallel to the Cu-O planes. The crossing lattices exist for high anisotropy $Bi_2Sr_2CaCu_2O_8$ (BSCCO) single crystals when the magnetic field is tilted between the c-axis and the layer direction and the phase boundary between them is complex.

We are focuses on vortex matter phases at very high in-plane magnetic fields. There is an additional focus on new ordered structures when 'decorated' chains (Josephson vortex (JV) stacks with attached chains of pancake vortices (PVs)) start to interacting at large in-plane fields. The first examples of vortex chains for highly anisotropic BSCCO single crystals superconductors at 85K were actually observed by Bitter decoration technique. As well, the interacting JV-PV structures (crossing lattices) were observed in very thin BSCCO crystals by Lorentz

microscopy [7]. Scanning Hall Probe Microscopy (SHPM) is a novel scanned probe magnetic imaging technique whereby the field at the BSCCO surface is mapped with Hall Probe heterostructure (Ga As/Al Ga As) which is capable of resolving a chain of vortices at the sample surface 85K. However, many researchers have used various different techniques. For example, in 2002, Buzdin and Baladie studied anisotropic $Bi_2Sr_2CaCu_2O_x$ (BSCCO) single crystals. The in-plane field $B_X = B\cos\Theta$ penetrates inside the superconductor in the form of JVs, while the perpendicular field $B_z = B\sin\Theta$ creates the PVs which interact with JVs via the Josephson coupling. As a consequently, they found the energy of Abriskove vortices (AV) in chain is lower than the energy of a single vortex. As well, when B_Z is applied, the vortices will start to penetrate in the form of chain especially with an increase Bz will then increase the number of chains without any changing in distance between the vortices in the chain. Buzdin and Baladie showed that PV stacks on a Josephson vortex have a long-range electromagnetic attraction due to their bending by JV currents. This attraction, in balance with a short-ranging repulsion,

provides an equilibrium distance between PV stacks with $\epsilon = \frac{\lambda ab}{\lambda}$ parameter characterizing the PV stack bending [8]. In the same year, Koshelev et al. (2002), showed that interaction between the pancake and Josephson vortices (JV) depending on the values of crossing fields and temperature and the behaviour of the decoration of Josephson vortices by pancake vortices in the single crystals of BSCCO using magneto-

optically [9]. The answer as to why GaAs/AlGaAs is better than Bi at low-temperature is as follows:

At low temperatures, the signal noise ratio is generally very high $\sim > 88$ times bigger than Bi. The maximum value of (I_{Hall}) for GaAs/AlGaAs is probably 40 µA at low-temperatures. The Hall sensor GaAs/AlGaAs exhibits the highest carrier mobility's$\sim 10^5$ Cm V^{-1} S^{-1}and lowest resistivity. Table 1 shows all details for both Hall-probe sensors at low-temperature.

Table. (1): **GaAs/AlGaAs Hall probe (HP) better than Bi-HP at low temperature.**

Parameters	Bismuth (Bi) at low temperature (4.2 K).	GaAs/AlGaAs heterostructure at low temperature (4.2 K).
Maximum value of Hall current (I_{Hall})	>100µA	40 µA
Mobility (µ)	200 Cm V^{-1} S^{-1}	10^5 Cm V^{-1} S^{-1}
carrier density for two dimensions (n $2d$)	8×10^{13} Cm^{-2}	2×10^{12} Cm^{-2}
Signal-to-noise ratio (SNR)	32×10^{-5}	2828×10^{-5}
Hall coefficient (R_H)	8×10^{-4}Ω/G	0.3 Ω /G

4. CONCLUSIONS

The interacting JV-PV structures by SHPM imaging for highly anisotropic $Bi_2Sr_2CaCu_2O_{8+\delta}$ (2212) single crystals at 85K was studied with a range of out-of-plane magnetic field 1.7 Oe – 6.8 Oe was studied. Through experiments on Bi-Hall probe at room temperature 300K and

imaging process by SHPM for BSCCO (2212) at 85K several points can be concluded as follows:

SHPM imaging has allowed us to demonstrate the behaviour of the decoration of Josephson vortices by pancake vortices in the single crystals of BSCCO at 85K. It was observed that the distances between chains decreases with increasing applied magnetic field (in-plane field) which also increases the density of chains until they do start to interact strongly as a result of interaction and attraction. Up to now scientists in the field have always assumed that the JV stack spacing only depends on $1/ (H_{II})^{0.5}$.

SHPM imaging has allowed us to demonstrate interacting crossing lattices of vortices in BSCCO (2212) single crystals under in-plane field and various out-of-plane fields. The long range attractions between Abriskove vortices (AVs) in the crossing vortex structure appear in highly anisotropic layered superconductors.

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