行政院國家科學委員會專題研究計畫 成果報告

異質結構超導與光子晶體的若干問題研究
研究成果報告(精簡版)

計 畫 類 別 ：個別型
計 畫 編 號 ：NSC 97-2112-M-216-001-
執 行 期 間 ：97 年 08 月 01 日至 98 年 07 月 31 日
執 行 單 位 ：中華大學電機工程學系

計 畫 主 持 人：楊宗哲

報 告 附 件 ：國外研究心得報告
赴大陸地區研究心得報告
出席國際會議研究心得報告及發表論文

處 理 方 式 ：本計畫可公開查詢

中 華 民 國 99 年 01 月 11 日

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執行年限: 97.8.1~98.7.31
NSC 97-2112-M-216-001

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民國九十八年十月三十日

中文摘要：

本計畫在 97 年度完成的結果，針對環狀多層周期結構之圓柱，以圓柱波的轉移矩陣法，就 TE 及 TM 波計算含有單一負材料或超導材料的光學性質，得到 $m \geq 1$ 模數存在有額外之高反射帶，利用此一特性可設計窄帶共振器，而不需引入缺陷層於結構中。對於次波長微波和特拉頻段在具有周期性凹槽的金屬線上之波導設計上，提出可使波強烈的局限在線上傳播，且損耗低。對於在鈮薄膜上做成全面或部分佈滿三角形晶格的孔洞形成的渦漩釘扎，由量得的磁阻曲線，呈現匹配高峯數後者比前者少，且與孔洞深淺有關。

關鍵詞：環狀周期層狀結構，轉移矩陣法，圓柱波，周期凹槽的金屬線，微波、特拉頻段，鈮薄膜，釘扎，磁阻，匹配場。

英文摘要(Abstract)：

In this report, we summarize our research results in 2008-2009. For annular periodic structure, the optical properties of the structure containing single negative material or superconductor are calculated by the transfer matrix method for TE and TM cylindrical waves. There exists an additional high reflectance band for the azimuthal mode number $m \geq 1$. This provides a new design for narrow band transmission filter or an annular resonator without introducing any physical defect layer in the structure. For subwavelength microwave and terahertz frequency guiding on the corrugated metal wire, a new design criterion is proposed and demonstrated to strongly confine surface plasmonic polarization propagate on the wire and to make the minima loss. For the full and partial triangular pinning hole array fabricated on Nb thin film, there exists the number of the prominent matching peak of the former one higher than that of the back one in the magnetoresistance curve. Such phenemon depends on the depth of holes.

Keywords：cylindrical wave, periodic corrugated metal wire, microwave, terahertz, Nb thin film, pinning, magnetoresistance, matching field

I. 簡介：

近幾年來光子晶體的最大進展是隱形方向的數值模擬和實驗。而在元件及量子計算亦是一直持續熱門的研究方向。另外，電漿子學也是很熱門的研究領域，由於它與奈米光學、積體光學有緊密的聯結。同樣地，電磁超介質材料的製作、模擬與理論的推展，使得該領域近一年有了廣泛的進展。

布拉格反射器或一維光子晶體是古老的研究課題，然而近幾年來，許多新奇材料的出現，人們想了解各種不同新奇材料組合的特性。最簡單及直接的方式，就是了解它們所形成的一維光子晶體的解析解，和數值模擬，可發現許多新奇的特性和功能，可開發出許多低成本的元件。並為推廣到多維光子晶體元件，輔上深入了解的動機和推展的路徑，以進一步了解多維度下，光子晶體的新奇特性。這就是本計畫在近一年裏，朝此方向研究的動機。經過一年的努力，已了解一維多層結構及二維環狀多層圓柱結構的特殊性質，並將這些成果發表於多種國際著名期刊。

表面電漿子在金屬線或金屬薄膜上，人們一直在尋求如何使它能在金屬線或薄膜上傳播更遠？而且頻率能夠降低，尤其能在微波或特拉頻段工作的夢想。在近一年的努力下，我們已找到方法，可使頻率降低到微波及特拉頻段的幾何結構，而且降低損耗的方法，這些成果分別發表於 OE，JEWMA 的期刊上。

在 Nb 超導薄膜上，打成不同幾何結構的孔洞，使之成為釘孔中心，作為再外加電流，量測磁阻的曲線所呈現的高峯現象，一直是人們想探討的特性之一。由於想製造渦漩元件，這是研究渦漩材料的方向之一。而且是由規則排列的釘扎轉變成異質結，進而轉成不規則釘孔排列所引起渦漩運動的轉變，有助於渦旋結構之相變遷問題的了解。近一年裏，完成(1)在 Nb 薄膜上佈滿或部分佈滿三角形晶格孔洞排列的渦漩釘扎的實驗量測。顯現臨界電流的不同溫度相依性。(2)比較三角晶格及蜂巢晶格釘扎所呈現不同的溫度相依特性，以分子動力學模擬解釋蜂巢晶格釘扎的鈮薄膜之匹配高峯出現在 $3.5H_1$，此處 H_1 是第一匹配場，這些成果均發表於 J.phys. 期刊上。

II.研究方法

(a).光子晶體

對於一維光子晶體(多層週期結構)均以轉移矩陣法處理。由於一維方法可在一般教科書看到，故不在此予以描述。

對於環狀多層圓柱結構，處理圓柱波從圓柱中央向周圍傳播的方法，最後會減化成徑向的週期結構，於是此部分亦可用轉移矩陣法處理。其詳細的方法描述可參考 M. A. Kali teevsti etal , J. Mod. Opt. 46, 875 (1999). 或 Mei-Soong Chen etal Phys. Lett. A373, 3594(2009).

對於次波長微波或特拉頻段(Terahertz)在金屬線上作成週期排列的凹槽形成表面電漿子的計算過程，可參考 Linfang Shen, Xudong Chen, 及 Tzong-Jer Yang, Optics Experess, 16, 3326 (2008); Jin-Jei Wu, Tzong-Jer Yang, and Linfang Shen, J. of Electromagnetic waves and Application, 23,11 (2009).

(b).超導薄膜上的週期針扎

對於解釋匹配場的數值模擬方法，可參考 C. Reichhardt etal, Phys. Rev. B58, 6534(1998); R. cao, Lance Horng, T. C. Wu and T. J. Yang, J. Phys. : condensed Matter 21, 075705 (2009).

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III.結果

(一).光子晶體部分

(1).環狀圓柱週期結構的光學特性的設計上，取得很新的結果，存在很好的應用潛能，值得未來二年繼續開發。此一成果發表於 Phys. Lett. A373, 3594 (2009) 及 Solid State Communications 149, 1888 (2009). 其成果主要為超導材料與介電材料作成環狀圓柱週期結構，發現 azimuthal mode 數≧1(對 TM 波)有額外高反射帶，且接近超導臨界波長處存在反射低值，此一結果可用於設計窄帶穿透濾波器或環形共振器(不需在結構上引入缺陷)。另一研究主題為含有單一負材料之環狀圓柱週期結構之光學性質，發現在 azimuthally mode 數≧1，且接近 Magnetic Plasma Frequency 及 Electronic Plasma Frequency(對 TE 及 TM 波)有額外高射帶，且當電漿子頻率落在光子帶隙內時，有反射低值。

(2).與吳謙讓教授合作發表多篇有關平面形多層週期結構方面的論文。例如:發表於 JOSA B26, 1141 (2009)的 "Angular dependence of a narrow reflection-and-transmission filter containing an ultra metallic film." 及 JAP 105, 0839178 (2009)的 "Extraordinary optical properties of a superconducting periodic multilayer structure in res zero permitiuty operation range." 這些成果，均以轉移矩陣法解析及數值模擬，均發現前人未發現的新成果，尤其是一些新現象和規律。

(3).表面電漿子方面的成果。

針對在金屬線上作成週期性凹槽，探討微波在其上的導引性質。在探討的過程中，發現設計準則，它不管是微波或特拉頻段都通用。對於外半徑為次波長大小，而其上刻有週期凹槽的金屬線，要把 spoof 表面電漿激子強烈地侷域在線上，發現要在凹槽處填加高介電物質，可使 spoof 的表面電漿子予以侷限在線上，即使頻率比漸近頻率低，而且表面電漿子的損耗很低，其所根據基本原理，在表面電漿子的色散曲線屬於 bound state，若欲將它與入射波耦合，需要入射光波的直線色散線與表面電漿子之色散曲線交叉或平移直線色散線。我們是採用後者的方法，但若在凹槽上填加高介電物質，則操作頻率可使之降低，但通常損耗大，結果發現一方面要將表面電漿子侷限在線上，又需損耗小，需要工作頻率接近漸近頻率，此一準則，可在微波及特拉頻段適用，此一成果已被推廣到金屬薄膜，這些成果發表在 JEWA 23, 11 (2009); Optics Express 16, 3326 (2008). JEWA 23, 2451 (2009). 也在 PIERS 2009 MOSCOW 會議作口頭報告，受到與會者熱烈討論。

(二).超導部分

此一部分延續過去幾年的研究所成果，繼續探討不同釘扎結構的釘扎現象，不管是實驗結果，理論上亦有進展。今年完成的工作有二方面，一為在超導薄膜上作成部份三角形孔洞週期晶格，另一個在超導薄膜上作成三角形洞週期晶格。看到後者有五個匹配高峯場，而前者看到二個或一個匹配高峯場，端賴洞之深淺，而且看到在零場下有負電阻出現的現象，此一結果尚需理論模擬，以了解其機制。

另一為在 Nb 超導薄膜上作成三角形及蜂巢釘扎週期晶格，探討釘扎隨溫度改變的情形。對於三角形釘扎晶格的薄膜，看到在臨界電流中突出的匹配高峯數在很窄的溫度範圍，隨磁場改變，從 6 個減少至 3 個，對於這種隨溫度變化的匹配效應在接近超導臨界溫度，因為相干長度急速地改變而造成，而對蜂巢釘扎晶格(與三角晶格，具有相同的釘扎大小和釘扎間距)而言，在 $H=3.5H_1$ 處出現明顯的匹配高峯，以分子動力學作模擬，以了解此一現象，得到渦旋的基態分佈可解釋此一明顯的匹配高峯。這些成果發表於 J. Phys. : Condensed Matter 21, 075705 (2009); J. Phys. : Conf. ser. 150, 052030 (2009).

IV.結論

對於環狀圓柱週期多層結構，以圓柱波的轉移矩陣法，得出不同二種材料而成的結構，均具有共同的特性，對 TE 及 TM 波在 azimuthal mode number m≥1 存在額外的高反射帶，此提供設計窄帶共振器，不需在結構中引入缺陷層。對於次波長微波和特拉頻段，在具有週期性凹槽的導線上的導引設計，提出一有效的方案，使之侷限在導線傳播和低損耗。

對於具有人工釘扎的週期排列於鈮薄膜上的釘扎效應的成果上(與洪連輝研究群的合作)，針對三角晶格釘扎全面或部分佈滿於鈮薄膜，量測磁阻，發現均有週期性臨界電流的高峯，但部佈滿的三角晶格釘扎的樣品，呈現的匹配高峯數較少，且與孔洞深度的釘扎有關，此一現象，尚未作出合理的解釋。

近一年在不同多層週期結構的光學特性上(與吳謙讓教授的研究群合作)，取得新奇及有規律性的成果。

V.感謝詞

一年來的研究成果豐碩，感謝國科會全力支持本計畫及能參與國際會議，短期訪問，從中獲得許多構想的研究主題，也有機會與國際友人建立研究夥伴的關係。也要感謝中華大學在研究的支持，使得能夠穩定推展研究。

Research Achievement of 2009

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(I). International conference and Symposium

1. **Session Organizer** in PIERS International conference 2009 in Beijing, China. (March 23-28).
2. **Invited Speaker** in The Seventh International Conference on New Theories, Discoveries, and Applications of Superconductors and Related Materials, May 13-16, 2009, Beijing, China.
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14. Jin-Jei Wu, Daru Chen, Kun-Lin Liao, **Tzong-Jer Yang**, and Linfang Shen, "A novel fiber sensor based on a Bragg fiber with a defect layer", Presented in 2009 Annular Meeting of Physical Society of Republic of China, National Chang Hua University of Education, Changhua, 2009,01,19-21.

(V). **Affiliation** and **honors**

1. **Investigator** of The physical society of Republic of China.(two year terms)
2. **Member** of AAPT(American Association of Physical Teachers).

3. **Member** of The Physical Society of Republic of China.
4. **Member of Sigma Xi.**
5. **Life member** of Material Science of Republic of China.
6. **Fellow of Electromagnetics Academy.**

訪問捷克科學院物理研究所

2008.7.30~8.6

楊宗哲

中華大學工程系

1.訪問經過

參加在荷蘭阿姆斯特丹舉行的第 25 屆國際低溫物理會議之前，先到捷克科學院物理研究所作一星期多的訪問研究。由於我與物理所的研究員 Dr. J. Kolacek 及 Dr. Pavel Lipavsky 的共同研究主題都是有關超導的問題，到達布拉格後的隔天，先與 Dr. Lipavsky 討論我的研究問題。然後再討論 Lipavsky 的研究主題－T 矩陣法(BCS 模型下)的修改，使超導與正常態自然地聯接在一起，解釋高溫超導的贋能隙。此一工作，他正與林佩貞討論，且將送到 PRB 審定中。所以，我們花了一天多的時間。而我所研究的主題是要以雷射脈波去激發高溫超導的 parent 薄膜的 John Teller 模，是這種相干性的高階聲子膜注入高溫超導薄膜裏，使該高溫超導因獲得更多相干性好的 John Teller 模，加強了電子－聲子的耦合作用，而預期會提升更高超導轉變溫度。他建議看 McGill 大學的 Prof。Carbortee 在 70 年代所計算的電子－聲子耦合常數，尤其是$\alpha^2F(\omega)$。不過，我認爲我所關心的是電子經由 high order harmonic ribration modes 耦合，而非電子藉由 harmonic ribration modes 之聲子耦合，其機制需重新探討。在這方面，Kolacek 沒有作出他的看法。不過，我這種看法最近由交大同事告知崔辜琪亦曾提及電子可能是藉由雙聲子耦合。也就是高溫超導的機制，會與聲子有關聯。

我與 Prof. Kolacek 討論他量測 Vortex Mass 的實驗進展情形，及量測 Vortex Mass 的原理和方法。他是採用電容法，二年多來，尙未有多大進展。另外，他還繼續推導超導的電場效應，他想從物理的最基本原理著手去探討，但亦未有多大進展。

在此訪問中，除了學術上的討論外，他們也帶我去捷克西邊的溫泉療養區及全世界唯二之無鉛水晶工廠(Moser)參觀，他們的工藝，除了保留傳統方式之外，仍與德國的 Messen 陶藝工廠合作，開發更新奇的優秀作品，使所生產的水晶維持高價位及高優值。所以其產品通常是歐洲皇宮貴族所喜好收藏，更是捷克總統贈送給外國元首的首選禮物。

2.訪問心得

在這次的短期訪問中，研究部份對我提高T_c的構想思考上，一方面擴大視野，另一方面對自己的構想更加堅定，並繼續發展下去。也期望 Lipavsky 能認同後，大家共同合作去開發。除了研究之外，看到捷克的人文優點，尤其在列強環伺之下，如何生存下去。他們對優秀傳統工藝－水晶，如何發揚光大及保持下去，這是值得我們學習。

3.感謝詞

感謝國科會支助這次的短期訪問。更要感謝捷克科學院物理研究所 Dr. Pavel Lipavsky 給予舒適的住處，讓我能夠欣賞到布拉格全市的美景，也要感謝 Kolacek 夫婦及 Lipavsky 帶我們去優美的溫泉療養區，欣賞美景及人們的優閒的一面。更難能可貴地看到 Moser 工廠生產無鉛水晶的工藝及成品。

訪問中國科學院物理研究所
顧本源研究群的報告

(2009.3.27~31)

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行政院國科會專題研究計畫編號
NSC 97-2112-M-216-001

I.訪問經過

我參加 PIERS 2009 Beijing 會議之後，就去中國科學院訪問顧本源教授之研究群，和他談論最近一、二年來的研究成果，及未來研究方向。一談起來，他就說近一年來因為肝腫癌問題困擾著他。然而，近來遇到貴人，使肝腫癌醫療問題得到解決，期望會有較佳進展。我五月份再去訪問他時，他的心情，晴朗多了，顯然已有信心解決此一問題。就因為身體的狀況，使得他一年來發表的論文數量減少了許多。但我查了一下，他發表的論文質量仍然保持很高(APL 論文數增加)。他又介紹他的二位學生與我認識及說明他們進展的研究狀況。他也帶我去見見他的研究夥伴楊國禎院士。他們目前正在發展他們二人以前發展的楊一顧反演方法推向負折射率材料的問題。相信 2010 年再去拜訪他時，此一方法應會有進展的成果。

II.訪問的研究內容

顧本源研究群最近著重在電漿子學方面的研究工作，他們在此領域近一年來完成幾樣值得一提的成果。

㈠在 n 型半導體次波長狹縫光柵中，以外加靜磁場以調節光穿透共振，利用 n-dopod 半導體的介電常數會隨外加磁場而變化的公式和性質，作成次波長狹縫的光柵，探討其光穿透行為會有如何的變化？他們發現在 Voigt 結構及 TM 偏振光的照射下，狹縫波導膜的二個穿透峯，會被偏移至較低頻率區，而且隨著磁場的增加，高峯的寬度會變窄。這種頻率的紅移現象，也會依賴磁場的分布結構。對於在外加磁場下，有效電漿子頻率的減小是主要負責這些效應的發生。他們將此一工作發表於 Optics Communications 281,6120 (2008)。

緊接此一工作之後，他們在 n-型半導體薄膜上作出二個狹縫，在 terahertz 頻率及外加磁場下，調節穿透場的近場分析，發現干涉圖樣的磁場強度高峯比零磁場增強兩倍。其來源是來自表面電漿激子和攸逝場的相互作用，也來自外加靜磁場引發改變表面電漿激子。

⑵二種組成物金屬/介電材料形成具次波長狹縫光柵之穿透共振。

光以很不尋常地穿過金屬薄膜上二維週期次波長洞的現象，引起人們的注目。又光通過在金屬薄膜上作成很窄狹縫的一維週期排列，也發現不尋常增大穿透性。這些不尋常的光穿透現象，其背後隱含的物理機制仍然存在爭論。在解釋這些現象含有二種型態的穿透共振，一為在金屬光柵的界面上，將表面電漿激子激發，另一為空氣狹縫可看作腔體，來自這種腔體的 Fabry-Perot 型波導共振。對完美導體結構而言，波導膜共振發生在 2h/n，此處 n 是整數，h 是狹縫深度。Q.Cao 及 P.Lalanne 討論在很窄狹縫之金屬光柵的穿透，認為不是來自表面電漿子，而是狹縫的局域波導膜造成穿透的不尋常放大。顧教授的研究群就在狹縫壁上多加了一層薄的覆蓋層而形成額外的腔體，在此腔體內的波導膜就會得到額外的穿透共振，他們以數值方法予以計算，並計算歸一化的磁場強度分佈印證此一

結論。此一成果發表於 APL 92,151901 (2008)。

III.訪問的心得

在這次訪問中，與他們交談之後，感到他們正在執行電漿子領域的計畫，所以談論中，一直在此主題上討論。我從討論中，想到自己曾研究過的不定性材料，若將極薄金屬薄膜層，換成 n-型半導體薄膜，則可藉由磁場來調變不定性材料的色散曲線，即從一類不定性材料變成另一類不定性材料。因此，我在未來的一、二年內將會著重此主題的研究。因為到目前為止，尚未有人發現可調變不定性材料的方法。

IV.建議

國科會多支持國內學者或專家到國外大研究群做短期或二星期內的訪問，能夠與自己研究的相關主題上，與他們作交流，多少會有收穫，亦有機會與他們建立合作研究的夥伴。

第 25 屆低溫國際會議報告

8 月 6 日~8 月 13 日,2008

荷蘭，阿姆斯特丹

楊宗哲

中華大學電機系教授

NSC 98-2112-M-216-001

㈠會議經過

此一會議是低溫物理領域大型會議，參與人數約四仟人之多，我 8 月 6 日從捷克，布拉格乘飛機到達阿姆斯特丹，入住旅館，然後去會場報到，拿到完整會議議程，就設定隔天及後續將聽的主題，由於同一時間，並排的節目很多，只好有些主題需捨取，而且有些論文壁報與一些國外專家學者約定會面討論，可說很忙碌。

這次會議，日本人有幾位得獎，且 Plenary talk 亦有好幾位，可說日本人在低溫物理領域愈來愈風光，難怪日本團這次龐大，連會議工作單位人士都跟我特別提及。看來台灣想在低溫物理出頭天，還早呢？

㈡會議內容及心得

此次會議我著重於渦漩運動及超導機制的主題，所以我的心得偏向於這方面的題目:

1. Joh Clarke 介紹 SQuid detected magnetic resonance image in microtesla fields，他講得極精彩，把微磁場在人體器官上應用的圖片放映，並說明如何需要多低的磁場才可以做到，他特別提及最近他們應用到醫學上新的診斷問題。
2. 我在最後一天早上去聽介紹如何以泛函密度方法應用到超導體的問題上，尤其對氫故態所預期的超導體溫度及外加壓力零奪大，給予第一性原理的計算值，此先前的預期更加接近實際的問題。同時，也舉出其他的例子說明此一方法的可靠性，令人吸引。
3. 這次碰到 Boris Shapiro，以色列 Bar Ilan 大學教授，他曾訪問交大，且研究過渦漩運動的問題，也曾研究超導的電場效應。他在此會議報告超導體在強電場下的奇異近鄰效應，與他約定在他的論文壁報處討論，並解說他的詳細過程，所以獲益較多。他們證明即使電場的極短穿透距離，也會強烈地影響超導-正常態之介面。他們利用 GL 方程式，輔以引入電場之邊界條件，以計算在表面上有序參數，分佈，表面能，超導的臨界約瑟芬電流，電壓-電流特徵。
4. M.Velez 主講人工磁性奈米結構之超導渦漩釘札，他將具有人工磁場結構的超導薄膜之渦漩動力學及釘札效應作了總結報告，讓人明白此一領域目前研究的狀況。因為此一報告與我們正執行的國科會計畫有緊密的關聯，所以會後，經過報告者同意給我他的總結報告紙本。
5. 在本次會議，我們報告的主題" Novel Pinning Phenomena in Nb Thin Films with the Heterostructure Pinning Arrays"，此一報告的論文，將附在本報告之後，作為附錄。

㈢建議

鼓勵年青學者多參加大型國際會議，與一些國外專家討論。而資深教授，應介紹這些年青學者與國外專家認識，以便建立合作管道。

㈣攜回資料

LT25 會議議程及會議論文摘要，這些資料有興趣的專家借閱。

Novel Pinning Phenomena in Nb Thin Films with the Heterostructure Pinning Arrays

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Abstract. Superconductor thin films with full or partial regular triangular hole arrays have been fabricated to explore the vortex pinning behavior. Electron beam lithography and reaction dry etching techniques have been used. The area of the regular square hole arrays is changed from 50um×50um for sample A to 50um×5um for samples B and C, and the area of the superconducting film remains the same. Magnetotransport measurements were carried out by a four-probe technique. Periodic critical current matching peaks are observed for all three samples. The small area hole arrays and their neighboring normal superconducting film without holes form heterostructure and novel pinning phenomena are observed. At certain temperatures, sample A has five matching peaks. However, samples B and C have two and one matching peaks, respectively. A strange phenomenon is observed that a negative resistance appears for the heterostructure films at zero field.

1. Introduction

Superconductors with periodic pinning arrays have been explored intensively through experiments and simulations during the past decade [1-10]. Square, triangular and hexagonal pinning arrays have all been explored with the help of modern nanolithographic techniques. Usually, these arrays are uniform all over the studied superconductor film. Some niobium thin films with spacing-graded arrays were studied by our group recently [11]. Those films are nonuniform, however, the pinning arrays are also over the entire superconducting films. In this research, we fabricate film with full area regular triangular pinning array and films with partial area pinning array. For the films with partial area pinning array, the pinning array part and its neighboring normal superconducting film without holes form a heterostructure. Some interesting phenomena are observed.

2. Experiments

Square arrays of submicrometer holes with a spacing of about 400 nm and diameter of about 200nm have been prepared on Si_3N_4-coated Si wafers using electron-beam lithography in conjunction with reactive ion etching. Then a dc sputtering completed the four-terminal geometry niobium films over the circular-hole array with a thickness of about 100 nm. This process is similar to that published in our previous reports [4]. Figure 1 shows a scanning electron microscopy (SEM) micrograph for part of the triangular array of corrugated pinning sites. MR measurements were carried out by a four-probe

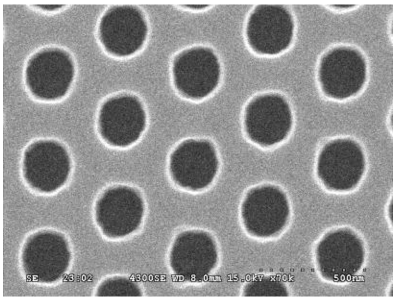


Figure 1. SEM image of the Nb film on top of the hole array after patterning. The pinning sites spacing is about 400 nm and the pinning

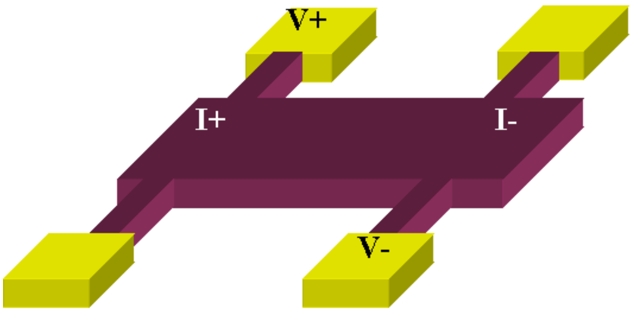


Figure 2. Sketch of the measurement setup.

technique in a superconducting quantum interference device (SQUID) system with a temperature fluctuation within 3 mK and the external magnetic field was applied perpendicular to the plane of the film and transport current. The voltages are measured at the opposite sides of the sample as shown in figure 2.

Three different samples were prepared. Sample A is with a 50um×50um pinning array and sample B and C are with 50um×5um pinning arrays. The area of pinning sites in sample B and C are only ten percent of total film area. The difference between sample B and C is the etching time. The etching time is 1 minute for sample B and 30 seconds for sample C. Figure 3 is the sketches of these samples, showing the distributions of pinning sites clearly.

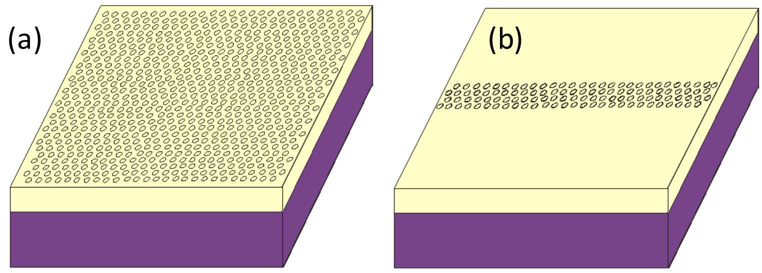


Figure 3. Sketches of the samples, showing the distributions of pinning sites in (a) sample A (b) sample B and C.

3. Experimental results

Figure 4 shows the normalized critical currents as a function of the magnetic field for the three different samples. These curves show a set of maxima of critical currents at specific value of external fields. There are five matching peaks for sample A at the observed temperature. These intervals between two consecutive maxima (H_1) are about 150 G. The experimental results of H_1 are in good agreement with the calculation based on the geometry of triangular unit cell of the pinning sites. Therefore, the vortex pinning can be strongly enhanced when there is a geometric matching between the vortex lattice and the pinning arrays. The critical temperature for sample A is 8.15K. The critical temperature for sample B and C is 8.51K. To have a reasonable comparison for the results of these samples, we select the same reduced temperature T/T_{c0}, which is about 0.985.

As shown in this figure, although sample B and C are with pinning sites for only a small part of the total area, they still have obvious matching effects. The first matching field is also determined by the density of the regular pinning sites. All the samples have the same H_1 about 150G. The reason is that the pinning enhancement in the pinning area for samples B and C determines the pinning effect for the whole film. However, the total numbers of the matching peaks for sample B and C are much fewer

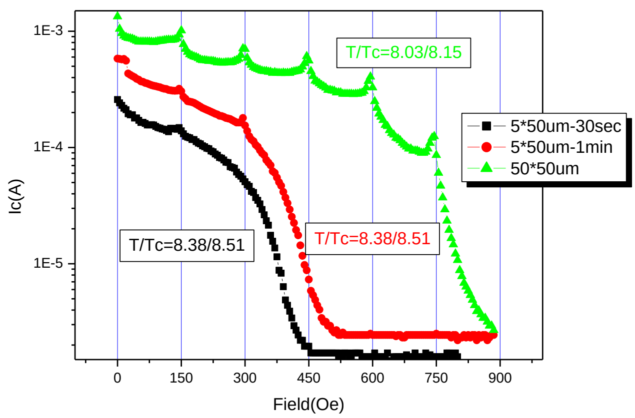
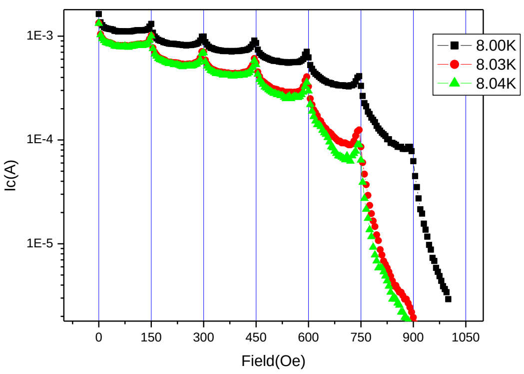


Figure 4. Critical current as a function of the magnetic field for Nb films with a triangular array of pinning sites.

than sample A. There are only two matching peaks for sample B and only one for sample C. It shows that pinning effect is greatly affected by the total number of pinning sites. The pinning sites in sample B are etched for 1 minute and the pinning sites in sample C are etched for 30 seconds. It is a natural result that they have similar curves for critical current's dependence on magnetic field, but the pinning effect for sample C is weaker. It seemed that the curve for sample C is a down shift of the curve for sample B.

Figure 5 show the temperature dependence of the critical current to magnetic field relation for sample A and B. It is clearly seen that sample A has many matching peaks. But with the increase of temperature, the number of matching peaks reduces from six to five. One of our similar sample shows that matching peaks reduces from six to four when temperature reduces form 8.02K to 7.97K. For sample B, there are always two matching peaks for a relatively wide temperature range. The temperature is an important factor in determining the number of matching peaks for sample A but not an important factor for sample B. The reason may be that the global pinning in sample B is already weak so that the increase of penetration depth of vortex does not affect the individual pinning of vortex very much. The situation is different for sample A. The penetration depth of vortex increases dramatically with the temperature increasing close to the critical temperature. This affects the pinning of individual vortex very much and hence reduces the number of matching peaks. This difference may imply that the local analysis is invalid for the heterostructure type samples such as samples B and C.

(a) (b)



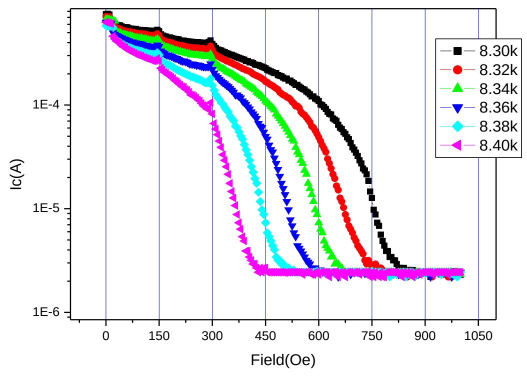


Figure 5. Critical current as a function of the magnetic field for (a) sample A and (b) sample B at different temperatures.

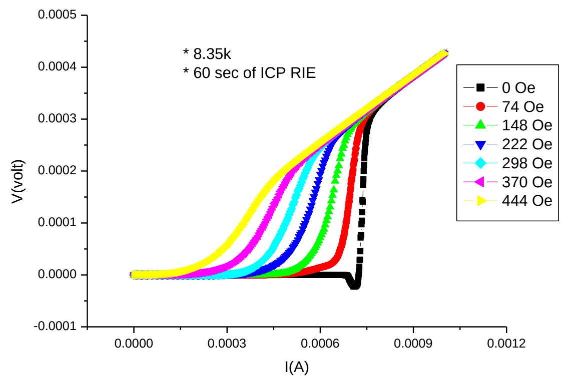


Figure 6. I-V curves at different magnetic fields for sample B at 8.35K. The first matching field is 148 Oe, so the magnetic fields here are 0.5, 1,1.5, 2, 2.5, 3 matching fields, respectively.

Figure 6 is the I-V curves at different magnetic fields for sample B. There is a negative dip at zero field. The current is applied along the long side of the pinning array. The voltage is measured at the opposite side of the short side of the pinning array as sketched in figure 2. If voltage is measured at the same side of the short side of the pinning array, this negative dip will disappear. This is an interesting phenomenon need to be explained.

4. conclusion

We have investigated vortex pinning in superconducting films with triangular array holes. The area of the regular square hole arrays is changed from 50um×50um for sample A to 50um×5um for samples B and C, and the area of the superconducting film remains the same. Obvious matching effects are observed for all the samples, whether full or partial areas are etched with pinning sites. The different temperature dependences of critical currents for these two kinds of samples are observed, which imply the special characteristic for the heterostructure samples. Negative resistance is observed at zero field in I-V curves for the heterostructure samples.

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國科會出席 PIERS2009 北京國際會議報告

98 年 4 月 14 日

報告人姓名	楊宗哲	系所 職稱	電機系 教授
會議 時間 地點	2009/03/23→2009/03/27 中國北京	本校核定 補助字號	(98)中華研國字第 36 號
會議 名稱	（中文）電磁學研究進展研討會 （英文）Progress In Electromagnetics Research Symposium		
發表論文 題目	（中文）一種新型帶帶隙濾波器基於 Bragg 光纖橫向共振結構 （英文）A Novel Band-rejection Filter Based on a Bragg Fiber of Transversal Resonant Structure		

報告內容應包括下列各項：

一、 參加會議經過

在 3 月 22 日早上 9:50 乘包車子到桃園中正機場搭下午 1:00 的中國國際民航班機直飛北京。在下午 4:30 左右到達北京，然後先去餐館吃晚餐後到 PIERs 會議會場，並入住中苑賓館，完成報到手續，並規畫隔天要聽的演講。

此次會議參與人數約五、六百人，其中台灣參與人數約 24 人左右，台灣人士主持五個 Session，也組織四個 Session，算是台灣人士在此會議扮演著重要的角色。主持五個 Session 之主題為：1.Electromagnetic Field in Bio-magnetism materials and instrument and Dispersion in cloaks and Metamaterials. 2.Meclical Electromagnetics , RF biological effect. 3.Plasmoniccs Nanophotonics（理論與實驗). 4.Electromagnetic Field in Materials and EM field Dispersion in clocks and photonic crystals. 5.Electromagnetic wave App;ications in Material Processing and characterization.由於每天有 8 個 sessions 同時舉行，使得只能挑選幾個有趣的主題去認真聆聽，此次會議，除了自己要上台講的主題外，我較專注於太陽能電池相關的講題及隱形(cloak)的問題。因此，在與會心得部份，就以這類問題來寫。

二、 與會心得

會議的第一天 3 月 23 日的演講主題很精彩，我先就香港科技大學 C-T . Chan 教授講"Dirac Spectra in Plasmonic systems : Honeycomb and Triangular Lattices." 主題予以大略陳述他以 graphene 二維電子特性之類比性，探討二維光子晶體內 Dirac Spectra 發現當引入時間反演破缺時，Dirac-point-derived-edge states 出現奇特的傳輸性質，在二維光子晶體中，因為散射光子的耦合導致 Dirace 色散譜，他在此演講中，針對金屬奈米球排成 honeycomb 晶格及三角晶格形成的電漿子能帶結構的不同性，給予清楚講述。電漿子晶格是開放系統，支持著 guided modes 及 leaky modes。他們發現當在半無窮或有限系統存在 edge 時，會有 guided modes states，對於 honey comb 晶格，存在 Dirac-point-derived-edge states 的條件也推導出來。

台大的陳瑞成發表一個 electric dipole emitter 放在一對金顆粒間，假定此 emitter 為二階自發幅射，他們模擬的結果呈現一對金奈米顆粒對自發幅的影響端一對金奈米顆粒的半徑及間隙，也依賴著 emitter 的吸收及釋放譜。另外，自發幅射的壽命大大地減小，其原因歸因於電耦矩與奈米對間的能量轉移造成。

Po-Tsang Wu 探討金屬-介電質介面的表面電漿波的問題得到一些有趣的結果。他們以金、銀及空氣、水、玻璃做為介電質為研究對象，發現治凸介面的表面電漿波(SPW)的相速度總是大於平面的 SPW，而凹形介面的 SPW 之相速度却比平面型介面之 SPW 相速度遠快。而對衰減常數面言，不管凸或凹都比平面型來得大，其原因是能量以徑向輻射到周遭介質中。

台大化學系 R.S. Liu 講金奈米結構的不同合成的路徑，其內容精彩豐富，他們找到合成的條件，可產生不同形狀金的奈米顆粒，提供改進光學性質的奈米材料的機會。

台灣師大物理系 Shu-Fen Hu 講述矽量子點太陽能電池，它在電極間擺成一串三個量子點，他們發現量子點捕捉光激發的載流子引起的光電效應，產生電晶體的 source-drain 電阻的變化，且其光導檢測元件的效率很高。

清華大學物理系 S.L Chang 教授研究群以 x-光波在矽晶(12 4 0)原子平面作為 x-光反射鏡，且在它的二個相鄰的晶面形成 Fabry-Perot 共振腔，他們以理論及實驗結果相互印証。

Ganquan Xie 在我們主持的 Session 中，就他們多年來發展的 Global 與 Local 電磁場(GL)的方法應用於超介質材料的隱形設計，其隱形設計方案是採用特殊的坐標轉換於 GL 模型中。他們的 GL 轉換模型可用於發現新的超介質材料結構及其性質。

在本次會議中，我們以三個主題講述一年來的 Bragg 光纖之新結構及其可能應用，吳俊傑教講 Bragg 光纖之光蕊改成二維橢圓孔光子晶體結構，在孔與孔之間距小於 Bragg 光纖之操作波長下，顯現高度雙折射效應。另外，二個主題是在 Bragg 光纖中引入一缺陷層，發現橫向的 Confinement loss 會有選擇性的波長呈現高峰，利用此一性質，只改變缺陷層的厚度或折射率而作為感測元件，其靈敏度遠比只在光蕊改變折射率還大，更比沒有缺陷層的 Bragg 光纖之感測元件還大，因此，我們的感測元件可資應用的範圍更廣。

中山大學 Yen-Chung chiang 提出改進有限差分頻譜方法，並應用於任意形狀的二維光子晶體問題，算是較為奇特的方法。

三、 考察參觀活動(無是項活動者省略)

四、 建議

NEW3SC-7

第七屆國際超導及相關材料新理論、新發現和新應用 會議報告

北京，5/13~16,2009

楊宗哲，中華大學電機工程系

Nsc 97-2112-M-216-001

(一) 會議過程

此一會議是每二年舉行一次。這次在北京舉行，正值 H1N1 流感的傳染，造成一些人投稿却不能來參與盛會，使得本次會議大約 200 人參與，此一人數是由第一天會議(5 月 14 日)早上之開幕式估計。

我是從會議議程上知道 5 月 13 日是報到日，隔天會議才正式開始，所以我就選在 5 月 13 日下午 1 點的中國國際航空公司的飛機直飛北京，到達北京約下午 4:30，而後乘首都機場巴士到中關村四橋路終站，正好在科學院物理所旁邊，而我住在物理所之物科賓館，每天從此處到會議處所 Double Tree Hilton 約需 1 小時。正好會議期間，天氣涼爽，除了其中一天(5 月 14 日)稍冷之外。

5 月 14 日早上正式會議開幕，緊接 Plenary 演講(25 分鐘)集中在一間大會議廳裡，分別由 R. Klemm,H. C. Ku,Davor Pavuna,N.C. Yen,及 M. Delano 主講。其中 N.C. Yen 講述在 High-Tc cuprate superconductors 中，competing order-induced pseudo-gap 現象及 vortex-state charge modulations 較為精彩。下午也安排 Plenary talk，分別由 Sung-Ho Selk, John D.Dow, N. Miyakawa, C. S. Ting, 及 Y. M. Malozova-Ky 主講，高溫超 導的普適性行為，著重於決定高溫超導中之 spin 與 charge dynamics 的相互作用。C. S. Ting 主講以 FeAs 為基之高溫超導體中 local impurity state S-S 成對對稱的訊號。5 月 15 日分成三個房間進行三個 Session 討論，而最後一天(5 月 16 日)早上就分成四個房間進行四個 Session，此時聽眾減少太多，等到最後頒獎給青年創意獎，科技創新獎及終身成就獎時，人數只剩下 30 幾個人而已。此次我推薦邀請演講的講員，交通大學電子物理系助理教授羅志偉得到青年創意獎(獎狀及 500 美金)

(二)會議內容

此次會議我著重於二個方面，超導機制及 vortex dynamics 的主題，所以我的心得就較偏向有關這方面的題目。

1. Honglo Yang 針對高溫超導體的 pseudo-gap 相與 particle-hole 對稱性問題以高精度 angle-revolved photoemission 及新的分析方法，確認在 pseudo-gap 相內，在 Fermi level 鄰近電子結構呈現 particle-hole 不對稱性，此支持 pre-formed pairs 沿著銅氧鍵方向。(銅氧超導體的 pseudo-gap 相中，存在 Fermi 面很大部份，在高於 Tc 仍然 gapped)

2. K. Hirata 主講奈米結構超導中 vortex matter，他講的內容豐富。他們作出低溫超導薄膜 Nb 及 NbN 作成 anti-dot lattice array，及在高溫超導 Bi-2212 薄膜上作

成 anti-dot lattice array，隨著 anti-dots 的直徑(r)及間距(a)變化量測 vorctex 之 flow-resistance(垂直於 array)。改變 r/a 比例產生不同的 vortex matching effect 通常的 matching 場在 Ho，而 fractional matching 在 Ho/2，Ho/3，2Ho/5....等。在低 Tc 超導，匹配現象相似於二維電子氣體系統處在晶格中，且在外加磁場的情況。anti-dot array 對渦旋來說，行同晶格，在這種情形，vortex flow resistance 相應於 Tc 附近的線性 GC 方程式的解，能夠把分數匹配效應產生及毀滅重現出來。在高溫超體，匹配效應緊密地關聯到一階渦漩晶格的 Meling(在存在 anti-dot arrays)及 vortex pinning 勢位的改變。而且，在高溫超導的 anti-dot array 引起 I-V 曲線的大非線性，此能用於產生大整流電壓，在外加 Biharmonic 電流下。

3.Meng-Bo Luo 主講第二類超導體中，驅動渦漩線之 creep，在具有點缺陷之第二類超導體中，彈性力與 random 釘扎力間的競爭，建立高度非線性能量的園地，控制著渦漩線的爬行。他們以大尺度的分子動力學的方式模擬，在 vortex glass(VG)與 Bragg glass(BG)二種結構下的 flux lines 的 creep 運動，得到在低釘扎力下的平均速度 v 正比於 $Exp[U(Fco/F)^{\mu}/T]$。發現 creep 運動有二個普適分類，$\mu = 0.5 \pm 0.02$ 屬於 BG，而 $\mu = 0.28 \pm 0.02$ 屬於 VG，BG 之 μ 值，大於 VG 之 μ 值仍因為 Vortex 在 BG 之運動中，Vortex-Vortex 相互作用力比較強，而造成較大的空間尺度形成有序的晶格。

4. N.C.Yeh 在 plenary talk 中,就氧化銅的高溫超導體的光譜證據，認為 pseudo-gap(PG)現象是 competing oder gap(CO)與超導的 gap(SC)(在 Tc 以上)二者之間的競爭所造成，而解釋了 hole-type cuprate 在 Tc 以上存在 Pseudo-gap(PG),而 electon-type cuprate 在 Tc 以上沒有 PG.(因為 CO<SC)

(三).建議

這次會議大會主席 J.D.Fan 來函希望我推薦台灣物理學界人士為 invited speaker. 我就推薦台灣師大光電所長吳謙讓教授及交通大學電子物理系羅志偉助理教授。其中羅志偉在這次大會中獲得 Youth Innovative award. 因此，我期望資深的教授只要有機會能夠多提拔中年青的專家學者，在一些國際會議中擔任要角，讓台灣學界能夠受到國際人士的注目。

(四).攜回資料

New3sc-7 會議手冊，它包含議程及參與者的論文摘要。

PINNING EFFECTS in Nb THIN FILMS with ARTIFICIAL PINNING ARRAYS

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Abstract: We summarize some results on the behavior of vortex dynamics and pinning effects in superconducting films with artificial pinning centers. Superconducting thin films with regular arrays of holes were fabricated using electron beam lithography and reaction dry etching techniques. Vortex dynamics in the mixed state in type II superconductors is strongly influenced by the presence of defects, which act as pinning centers. Periodic critical current matching peaks were observed in magnetotransport measurements. The matching effect is caused by the interplay between the pinning centers and vortex lattice. Therefore, vortex lattice behaviors are changed for different temperature and the geometry of the pinning centers. Molecular dynamic simulations are made to study this phenomenon. The ground state distribution of vortices obtained from simulations cans give a reasonable explanation of the prominent matching peaks we found in the experiments.

I. Introduction

During the past decade, the thin superconducting films with artificial pinning arrays are studied intensively by many research groups.[1-9] It is well know that above the lower critical field Hc_1 the magnetic field will penetrate into type II superconductors, and appear as vortex arrays when the field is close to the upper critical field Hc_2. By introducing artificial pinning array, which is usually periodic, many interesting and complex vortex dynamic phenomena appear due to the interaction between the vortex array and the periodic pinning array. One prominent phenomenon is the so called matching effect. When the number of vortex is an integer multiple or rational fraction of the number of pinning sites, the vortex array will match the pinning site array, thus the critical currents at these corresponding magnetic fields will have high peaks and the magnetoresistence will have low dips. We have made samples with relatively large pinning sites. Some special pinning phenomena are observed in films with square arrays and honeycomb arrays [10,11]. We made molecular dynamic simulations to study these pinning phenomena. It was found that the interaction between the interstitial vortices and the multivortices captured within the pinning sites has large impact on the pinning phenomena. The simulation results we obtained give good explanations to the experimental results and confirm that the ground state vortex configuration has close relation with the matching effect.

II. Experiments

In our experiments, the desired arrays of submicrometer holes were prepared on

Si_3N_4-coated Si wafers using electron-beam lithography in conjunction with reactive ion etching. Then a dc sputtering completed the four-terminal geometry niobium films over the circular-hole array with a thickness of about 100 nm. So there is no hole in the niobium film and the pinning sites obtained are close to blind holes. The pinning is mainly caused by the corrugation at the edge of the pinning sites. We have manufactured films with square, triangular and honeycomb arrays of pinning sties. This process is described in more detail in our previous reports [9]. MR measurements were carried out by a four-probe technique in a superconducting quantum interference device (SQUID) system with a temperature fluctuation within 3 mK. The external magnetic field was applied perpendicular to the plane of the film and transport current.

III. The experimental and simulation results for films with square pinning arrays

Fig. 1 shows the normalized critical currents as a function of magnetic field for three different samples. For sample A, the pinning sites spacing d is about 400 nm and the pinning site diameter a is about 120 nm; for sample B, d ≈ 500 nm and a ≈ 200 nm; for sample C, d ≈ 500 nm and a ≈ 250 nm. The matching effects are observed clearly in these figures. The first prominent peak is corresponding to the first matching field, which is in good agreement with the calculations based on the density of the pinning sites. The special phenomenon in Fig.1 is that there seems to be a missing peak in all three I_c-H figures. The third peak seems to be missing in Fig. 1(a). If observed closely, that peak is not missing but it is much lower than the second peak and has almost the same height as the fourth peak. Similar missing peaks are found in Fig. 1(b) and 1(c).

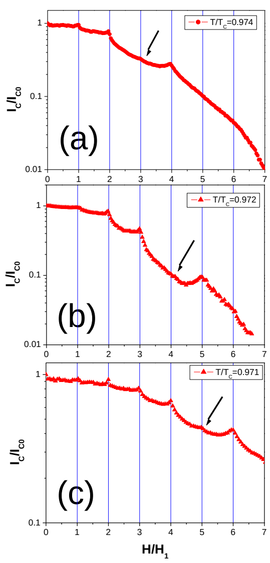

FIG. 1: Critical current as a function of the magnetic field for three different Nb films with a square array of pinning sites. For sample A, d ≈ 400 nm and a ≈ 120 nm for sample B, d ≈ 500 nm and a ≈ 200

nm; for sample C, d ≈ 500 nm and a ≈ 250 nm.

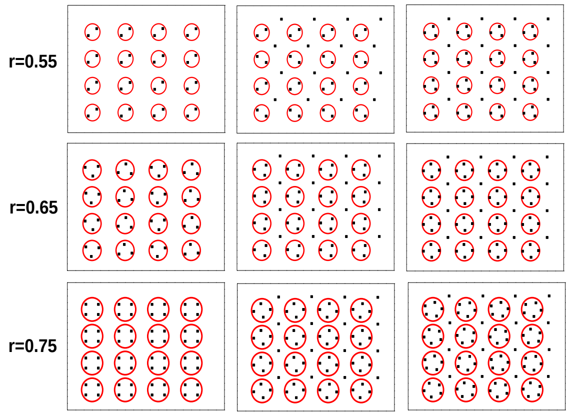

Fig. 2: The simulation ground state distribution of the vortices for different pinning site diameter and magnetic field: (a) r_p=0.55, H=2H_1 (b) r_p=0.55, H=3H_1 (c) r_p=0.55, H=4H_1 (d) r_p=0.65, H=3H_1 (e) r_p=0.65, H=4H_1 (f) r_p=0.65, H=5H_1 (g) r_p=0.75, H=4H_1 (h) r_p=0.75, H=5H_1 (i) r_p=0.75, H=6H_1. The circles represent pinning sites and the dots represent vortices.

We think this effect have close relation with the ground state vortex configurations and made simulations to study it. The simulation methods we used here are similar to those in [12] and our previous reports [10]. We model a 2D system with periodic boundary conditions in x and y with Nv vortices interacting with Np pinning sites. We numerically integrate the overdamped equations of motion:

$\eta \mathbf{v}_i = \mathbf{f}_i = \mathbf{f}_i^{vv} + \mathbf{f}_i^{vp} + \mathbf{f}_d$ Here, f_i is the total force acting on vortex i, f_i^{vv} is the force on the i^{th} vortex due to interactions with other vortices, f_i^{vp} is the vortex pin interaction force, f_d is the driving force and η is the viscosity, which is set equal to unity.

The ground state vortex configurations for different pinning strength and pinning size are given in Fig. 2. For rp=0.55, all the vortices are captured within the pinning sites at the second matching field. At the third matching field, because the pinning sites are already saturated, every interstitial position begins to have one vortex. The appearance of interstitial vortices is corresponding to the sudden drop of the critical currents in this case. At the fourth matching field, there is still one vortex at each interstitial position and the added vortices are pinned in the pinning sites. The critical current at the fourth matching field will be close to that at the third matching field, because each interstitial vortex is caged by similar forces from the neighboring pinned vortices. This is corresponding to the experimental results in Fig. 1(a). The simulation results for rp=0.65 and rp=0.75 are corresponding to the experimental results in Fig. 1(b) and 1(c). The explanations are similar to those for rp=0.55. The only difference is that more vortices are in the pinning sites for larger pinning site, thus the missing peak appears at higher magnetic field.

IV. The experimental and simulation results for films with honeycomb pinning arrays

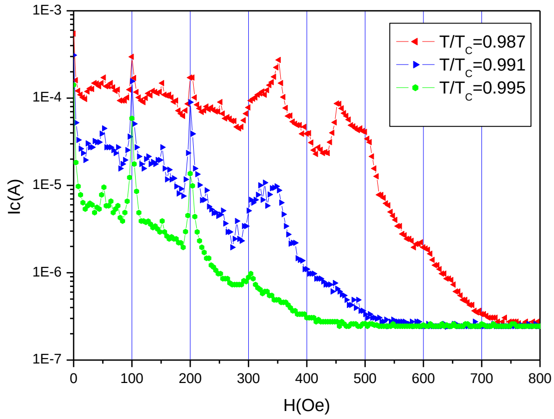

Fig. 3: Critical current as a function of the magnetic field for the Nb film with honeycomb pinning array at different temperatures.

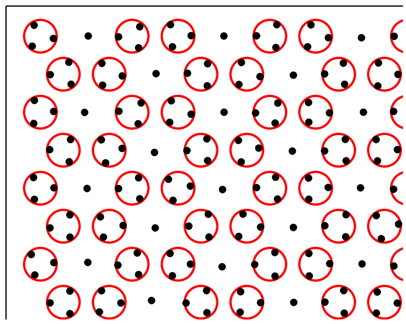

Fig. 4: The simulated ground state vortex configration for the Nb film with honeycomb pinning array at the third and half matching field. The circles represent pinning sites and the dots represent vortices.

The pinning effect observed in Fig. 3 is also very interesting. The matching peak at the third and half matching field at the lowest temperature is very high and as high as the peak at the first matching peak. There is no peak at the third matching field. The critical current increases when the magnetic field increases to the third matching field. However, after the third matching field, the critical current does not decrease as we expected, instead it increases until the third and half matching field. We made simulations about the vortex ground state at these fields to understand this special phenomenon. One thing to be noticed is that the ground state vortex configuration at the first matching field is a honeycomb array. The elastic energy of a honeycomb vortex array is much higher than that for a triangular array. The ground state vortex configuration at the third and half matching field is shown in Fig. 4. There are three vortices in every pinning site and they form an equilateral triangle. There is one vortex at each interstitial position, and the vortex at this site form six triangles with the neighboring vortices in the pinning sites. The elastic energy of the vortex array is not very high. Most of the vortices are pinned in the pinning sites and the pinning energy is fully exploited. Thus this configuration is very stable and the critical current is relatively high.

V. Conclusion

We made superconducting thin films with artificial pinning arrays and found special pinning phenomenon. In the film with square pinning array, matching peak seems to be missing at particular matching field, and this missing peak is at different matching field for different pinning sizes. In the film with honeycomb pinning array, the matching peak at the third and half matching is very high at low temperature. These interesting pinning phenomena are explored through molecular dynamic simulations. The simulation results we obtained give reasonable explanations to these experimental results. This confirms that the ground vortex configuration has close relation with the matching effect.

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