2018.05.23 고려대학교 물리학과 세미나

Flux pinning property of REBCO thick films with artificial pinning centers

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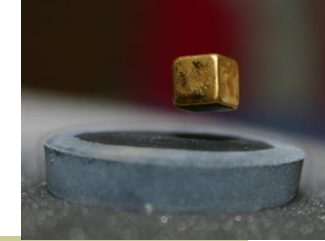
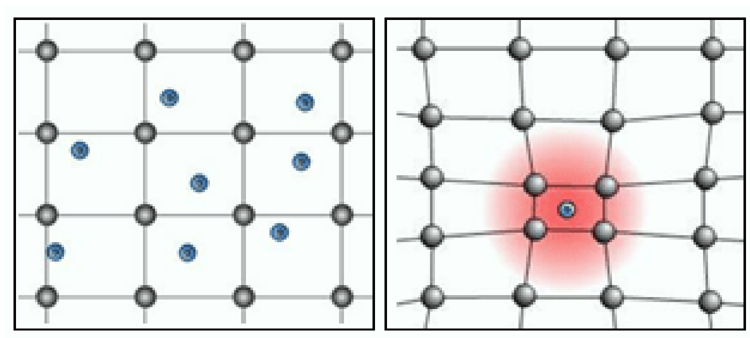
Department of Physics
Chungbuk National University

오래 써도 열나지 않는 휴대폰



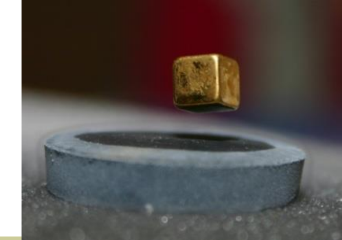
- 전기제품에서 열이 나는 이유 :

금속 내에서의 전기 저항: 자유전자가 격자진동, 물질내부 결함, 불순물등과 충돌하여 생김



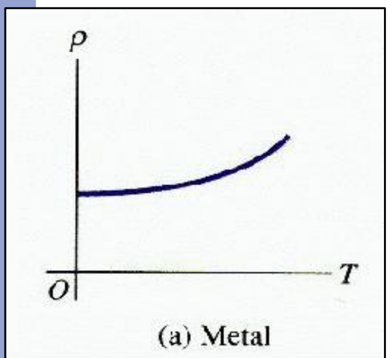
이러한 충돌 시 전자의 운동에너지 일부는 빛이나 열로 방출되는데 그 열의 양은 저항에 비례한다.

열 = (전류)^2 x (저항)

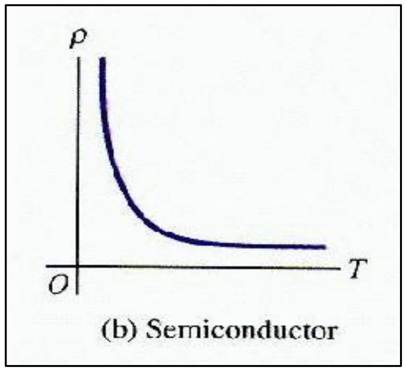


초전도 현상의 발견

저항의 온도 의존

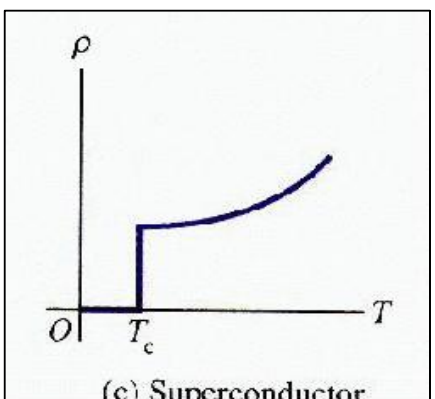


(a) Metal



(b) Semiconductor

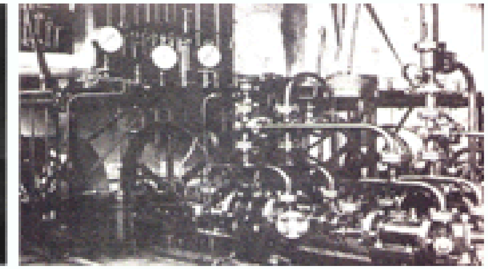
온도의 감소에 따라 감소　　온도의 감소에 따라 증가



(c) Superconductor

금속과 비슷하나 특정온도(Tc) 이하에서는 0

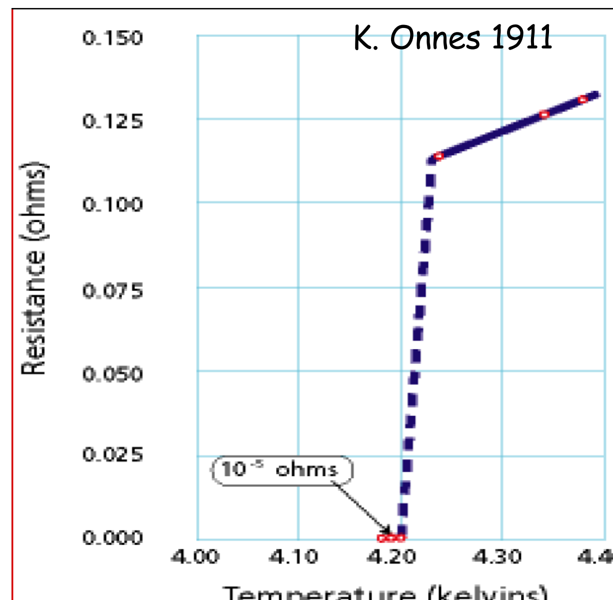
네델란드의 노벨 물리학자 온네스



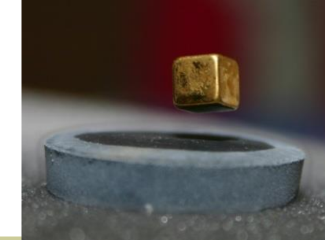
온네스의 실험기기들

1911년 네덜란드의 온네스가 수은(Hg) 에서 발견

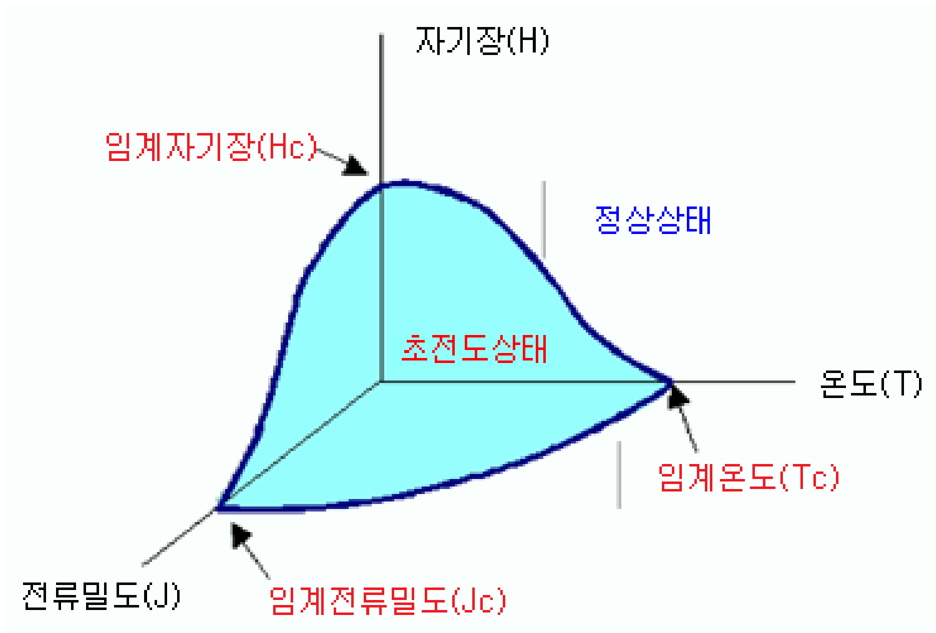
전기 저항이 0 이 됨 -> 전기전도도가 무한대가 됨



초전도 현상과 초전도체



- **초전도현상(Superconductivity):** 어떤 물질이 적절한 조건 하에서 물질의 전기저항이 완전히 사라지는 특성을 갖게 되는 현상



- **초전도체:** 도체 중 통전전류에 대한 전기저항이 전혀 없는 **'완전도체'**
- 도체: 열 또는 전기의 전도율이 비교적 큰 물질. 예: 구리, 철 등의 금속
- 부도체: 열, 전기의 전도율이 작은 물질. 예: 나무, 돌, 세라믹 산화물

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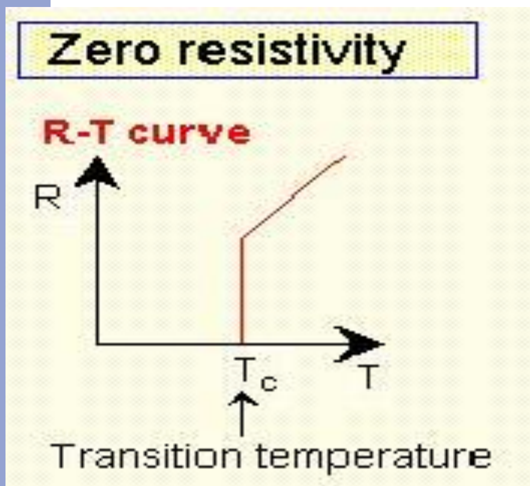
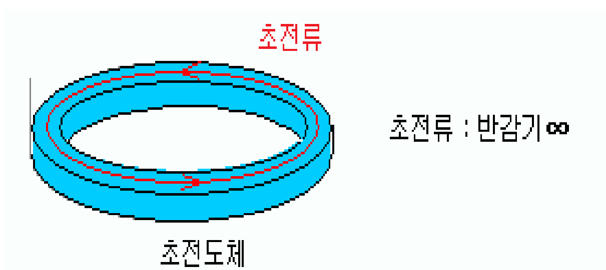
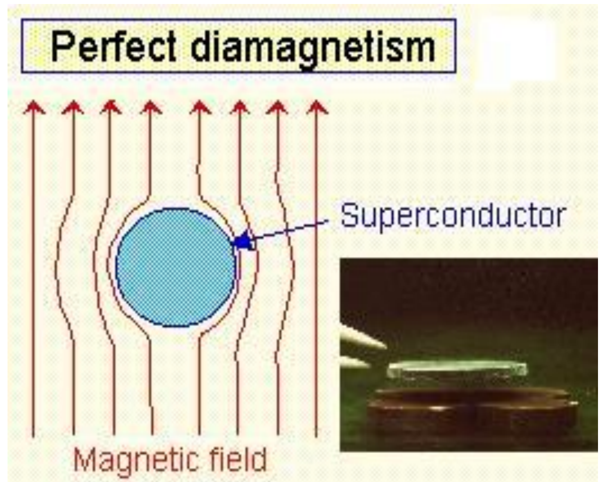
초전도체의 특성

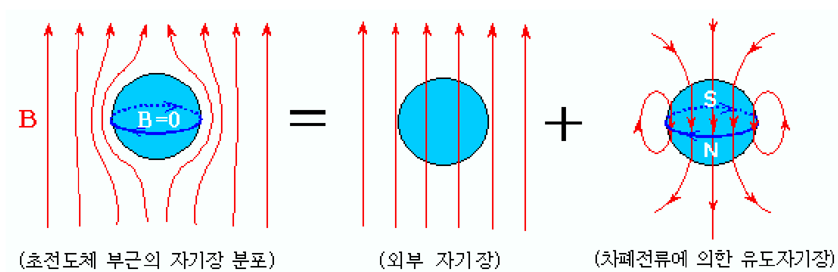
전기적 특성



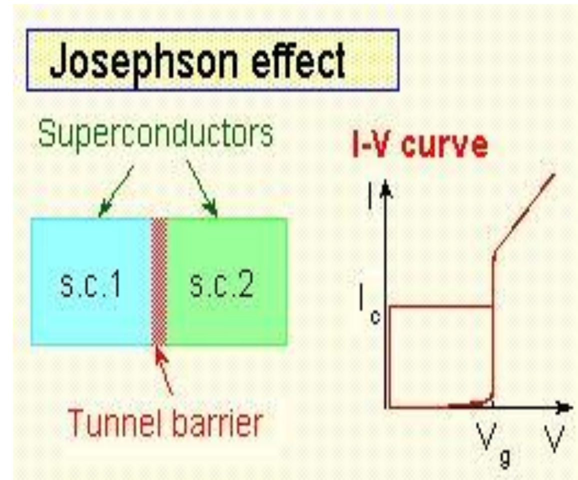


자기적 특성

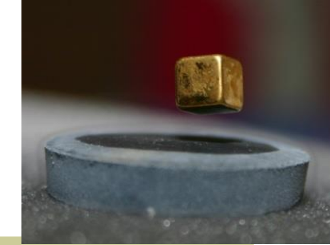




터널효과



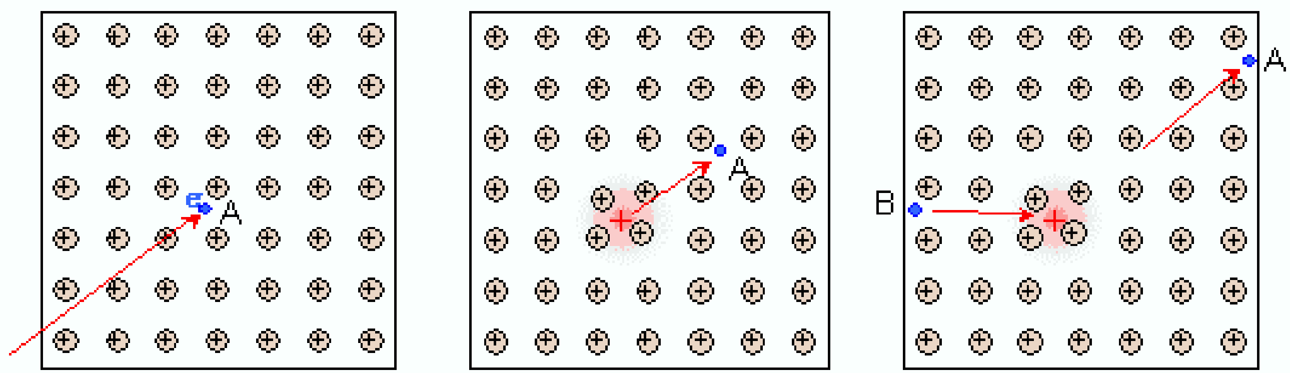
초전도체의 이론적 설명



1972년 미국의 노벨물리학상 수상자인
바딘 쿠퍼 슈리퍼

BCS 이론: 1957년 "J. Bardeen", "L.P. Cooper", "J.R. Schrieffer" (미국 일리노이 주립대학) 라는 3명의 물리학자들에 의해 이루어짐.

초전도 상태에서는 포논이 중간역할을 하여 전자들이 쌍(쿠퍼쌍)을 이룬다는 이론.



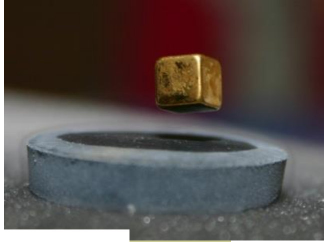
전자 A가 빨리 지나가며 양이온을 유인

굶뜬 이온들이 전자 A가 지나간 자리로 모여 양전기 형성

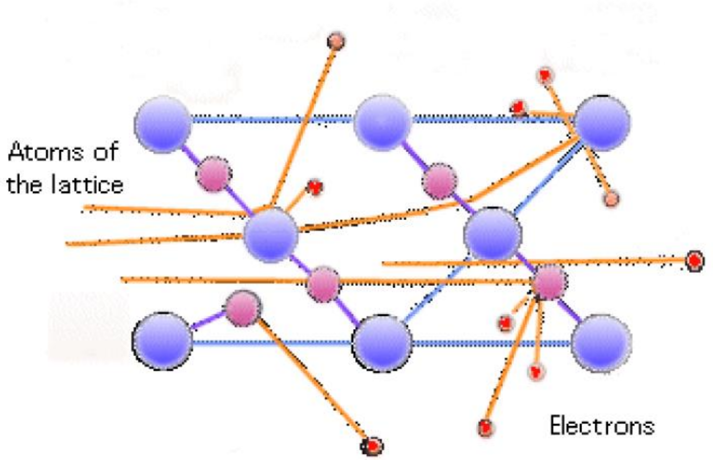
전자 B가 양전기 영역으로 끌려 들어감. 전자 A, B가 서로 당겨 쌍을 이루는 겉보기 효과

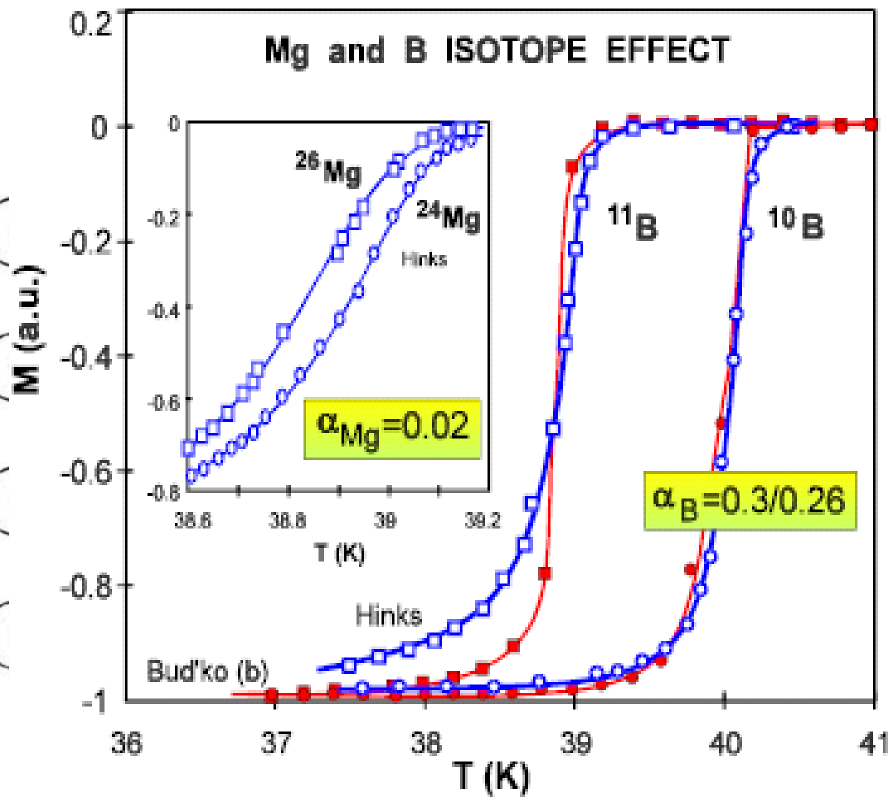
쿠퍼쌍을 이루는 원리

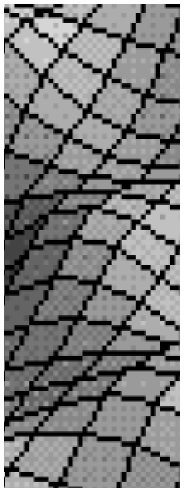
BCS 이론



일반 금속



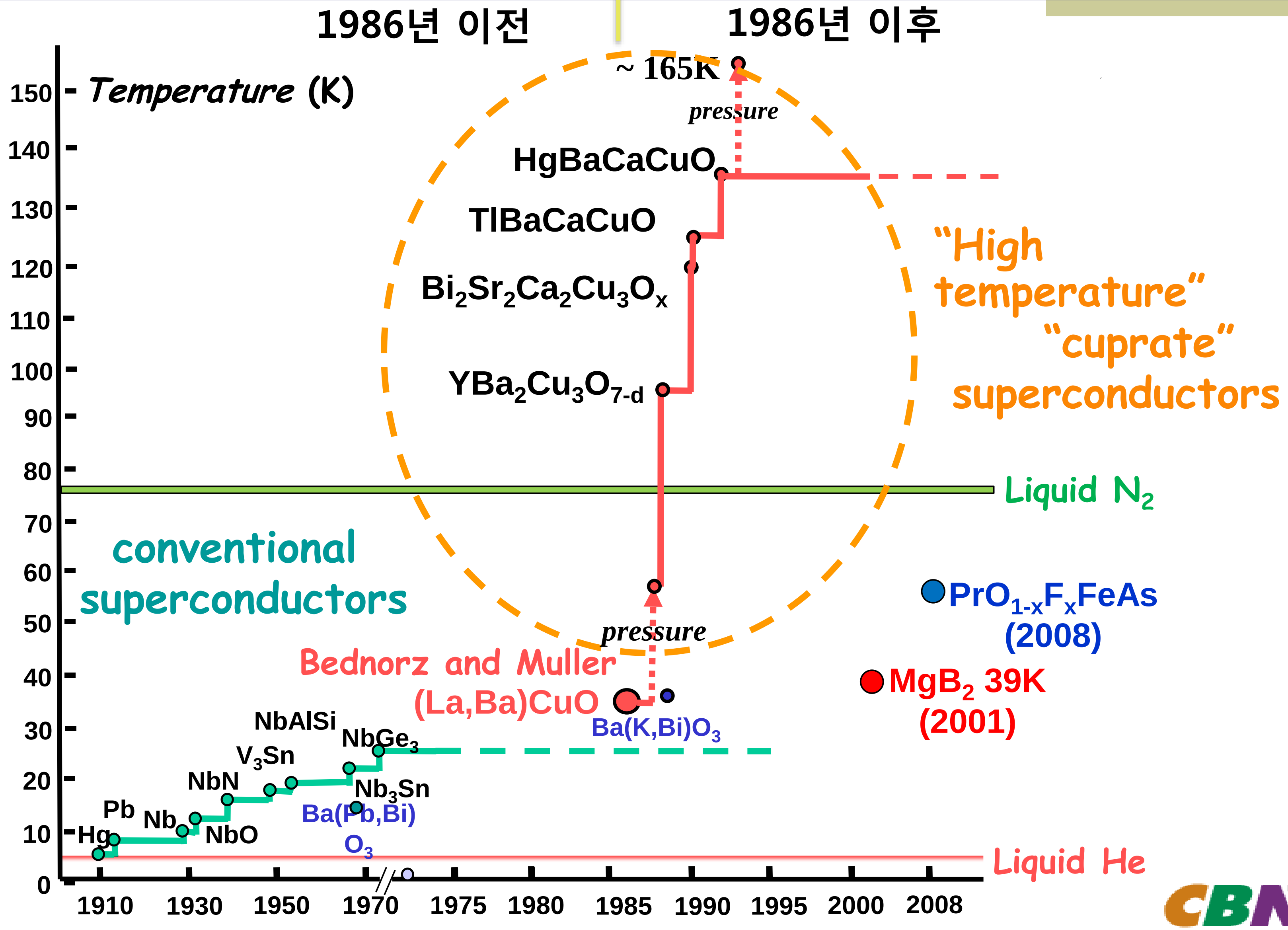




$T_c \sim M^{-\alpha}$ **: 동위원소 효과**

포논이 초전도 현상에 중요한 역할을 한다는 증거

초전도체의 임계온도 변천과정



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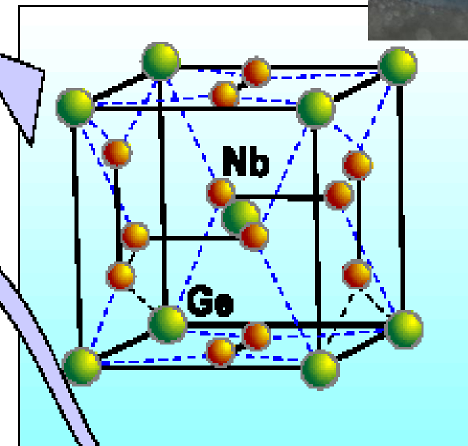
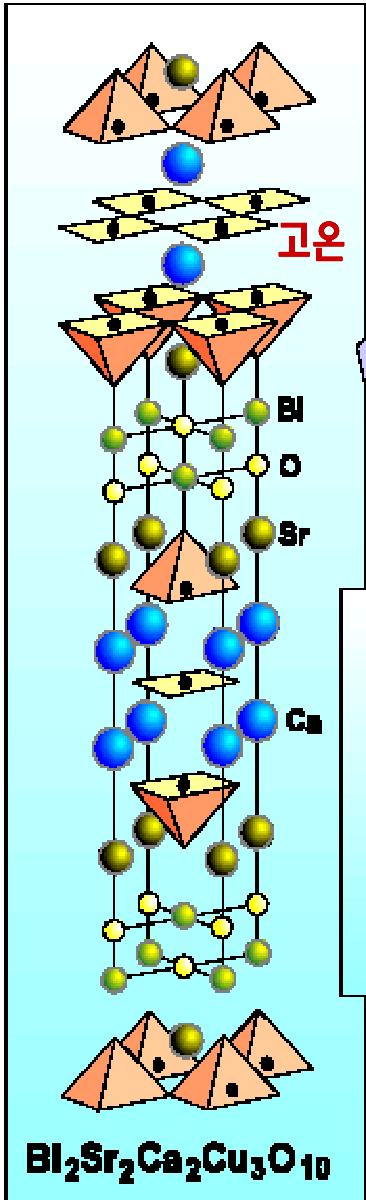
다양한 초전도체의 구조

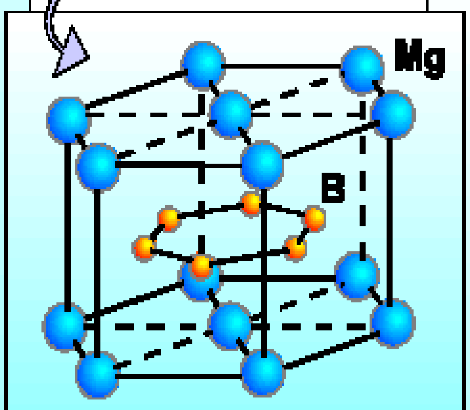
저온 초전도체

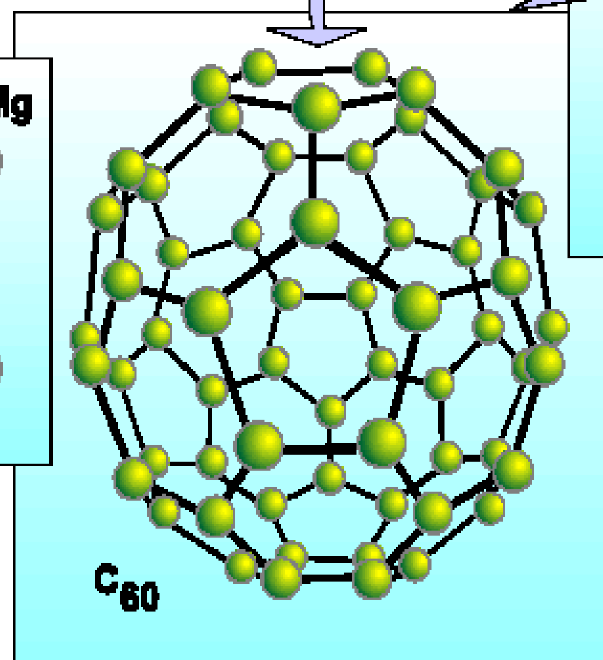
1. Simple metals
   (Nb, Tc=9K)
2. Alloys
   (Nb_3Ge, Tc=23K)
3. Organic superconductors
   (Tc=12K)
4. Molecular superconductors
   (C_{60} , Tc=52K charge Injected)
5. HTSC
   (Hg-1223, Tc=134K)
6. MgB_2, Tc=39K

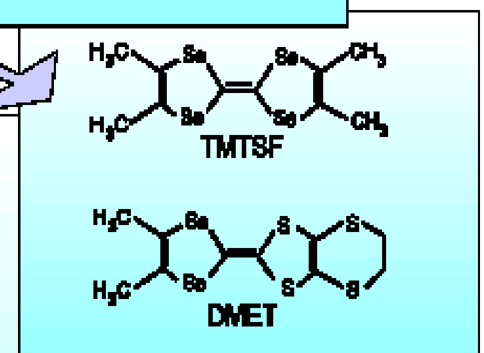


고온 초전도체

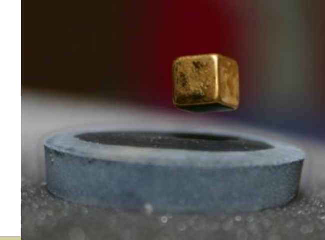








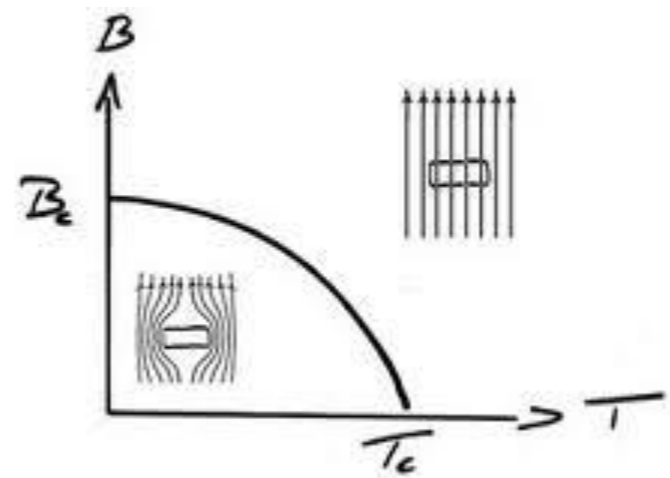
초전도체의 종류



1종 초전도체

$B > B_c$ 의 조건에서 초전도 현상이 사라짐

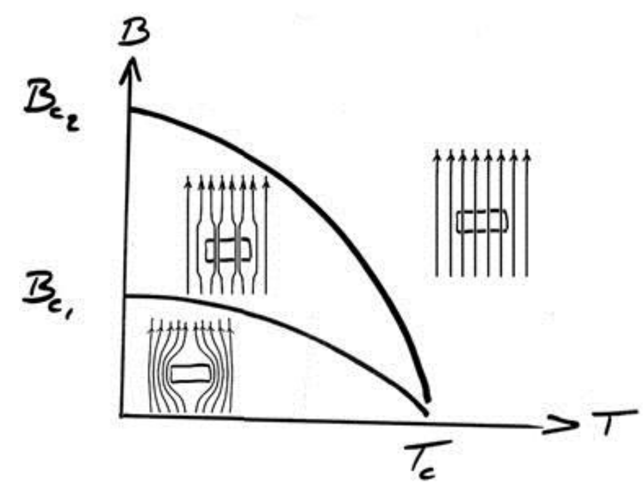
1종	Ti	Al	Hg	Sn	Pb
B_c (mT)	10	10.5	41.2	30.9	80.3



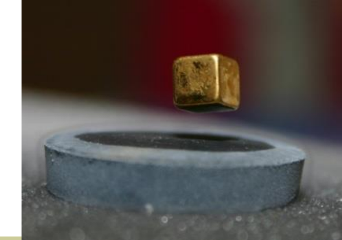
2종 초전도체

$B_{c1} < B < B_{c2}$ 인 구간에서 자기장의 일부가 자기 소용돌이 형태로 초전도체 내부를 통과하는 혼합 상태가 존재함

Nb(2종)	B_{c1}	B_{c2}
B_c (mT)	~170	~240

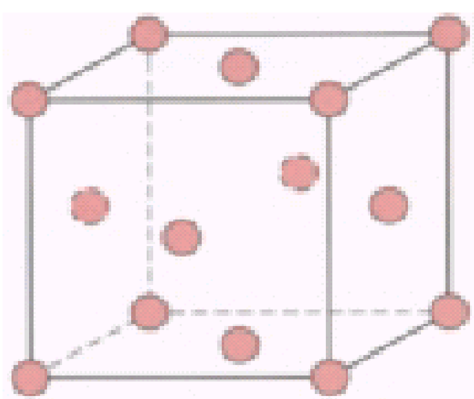


1종 초전도체와 2종 초전도체의 비교



1종 초전도체

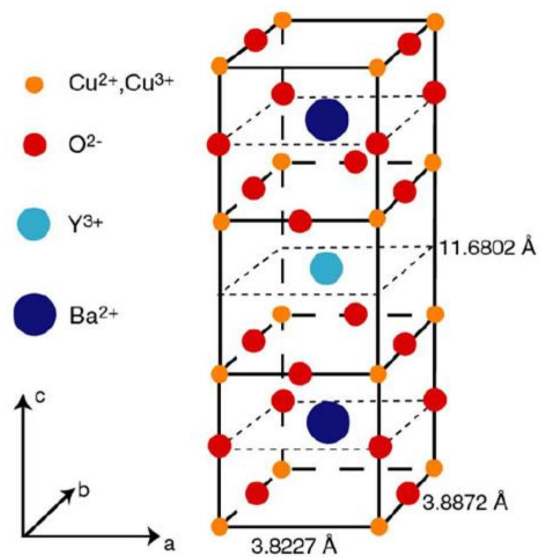
- 임계자기장 1개
- 낮은 임계온도
- 좁은 범위의 임계자기장
- 간단한 구조
- 금속원소, 이원자 화합물



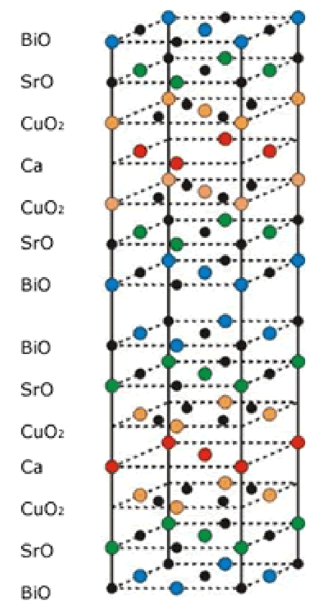
Cu

2종 초전도체

- 임계자기장 2개
- 원소의 결합에 민감
- 복잡한 구조
- 구조의 이방성
- 혼합상태의 존재로 균일하지 못한 초전도성

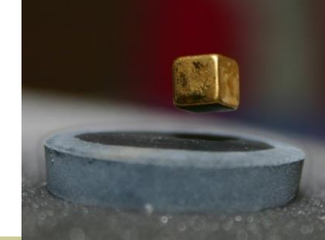


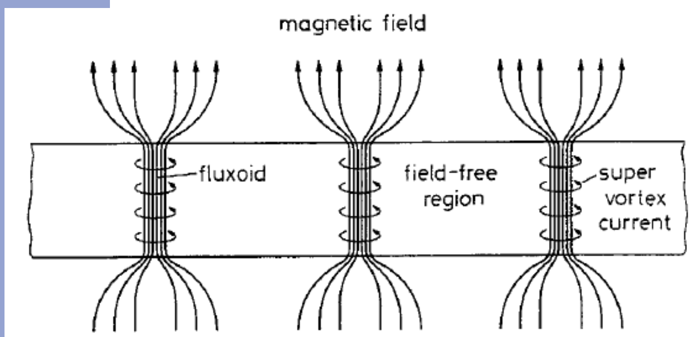
$YBa_2Cu_3O_{7-x}$

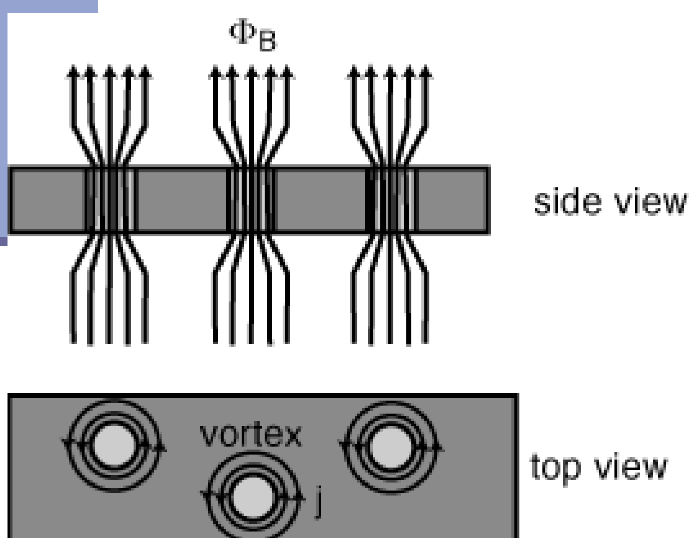


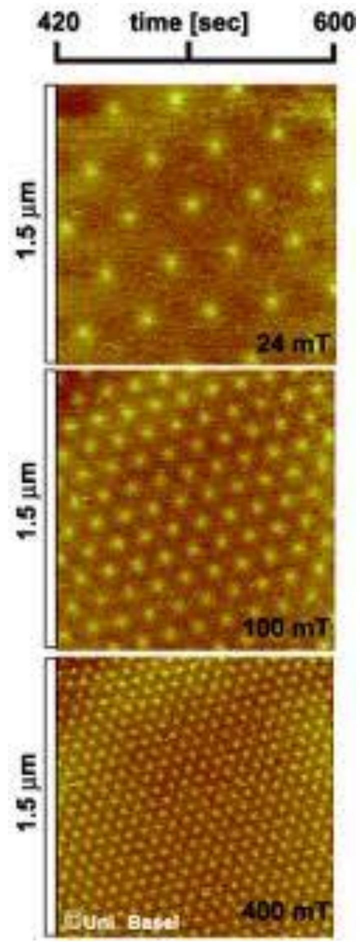
Bi-Sr-Ca-Cu-O

자기 소용돌이 (magnetic vortex)

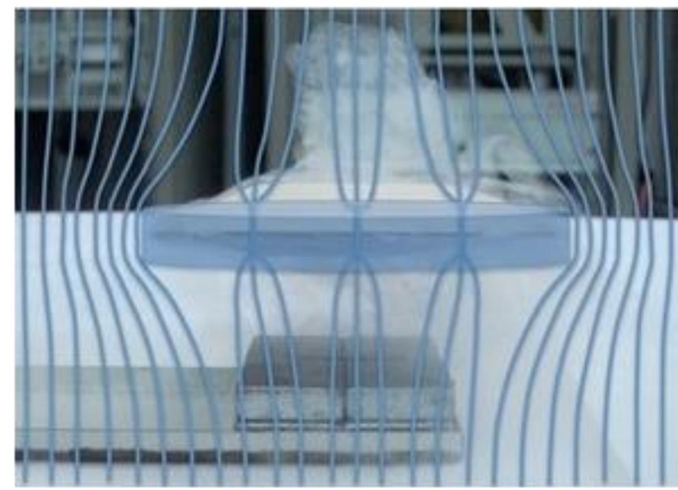






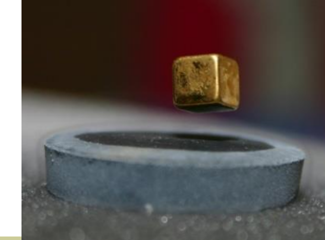


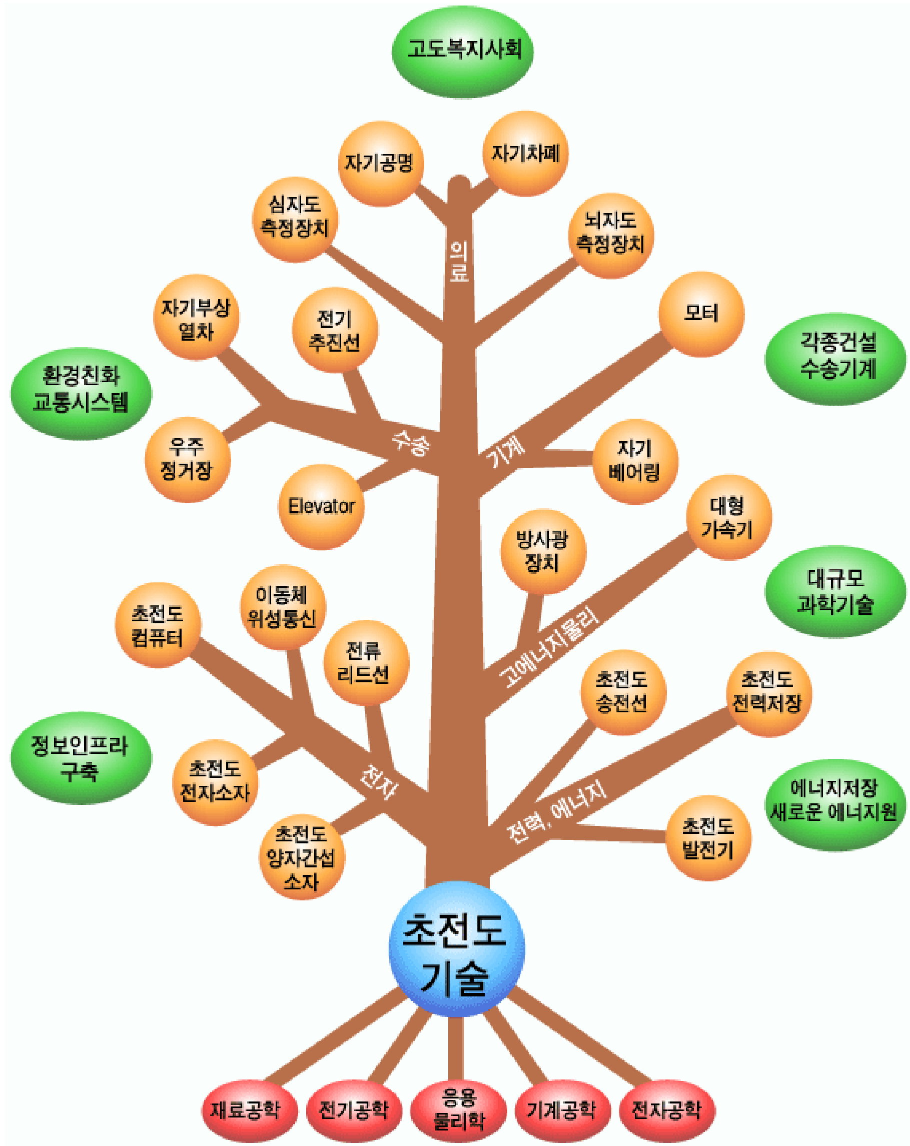
자기 소용돌이의 TEM 사진



2종 초전도체와 자석사이의
자기 소용돌이 그림

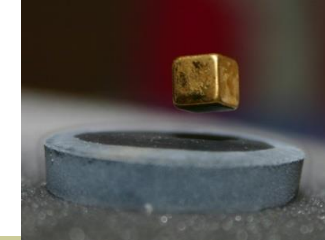
초전도의 응용분야

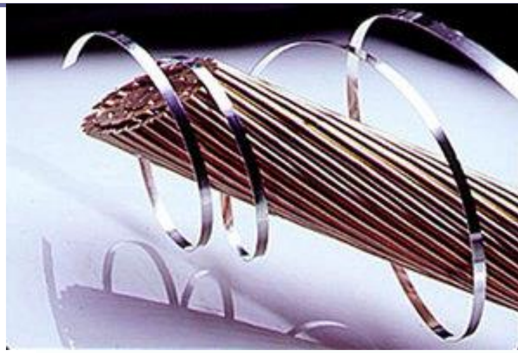




고도복지사회
자기공명
자기차폐
심자도 측정장치
뇌자도 측정장치
의료
자기부상 열차
전기 추진선
모터
각종건설 수송기계
환경친화 교통시스템
수송
기계
우주 정거장
자기 베어링
Elevator
대형 가속기
방시광 장치
대규모 과학기술
이동체 위성통신
초전도 컴퓨터
전류 리드선
고에너지물리
초전도 송전선
초전도 전력저장
정보인프라 구축
초전도 전자소자
전자
전력, 에너지
에너지저장 새로운 에너지원
초전도 양자간섭 소자
초전도 발전기
초전도 기술
재료공학
전기공학
응용 물리학
기계공학
전자공학

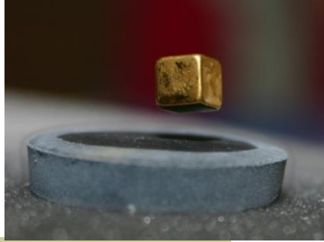
초전도 응용분야 - 전력

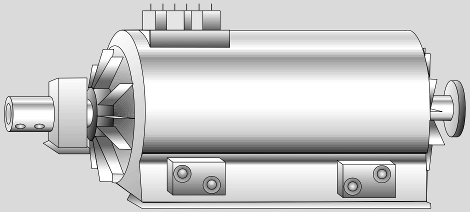


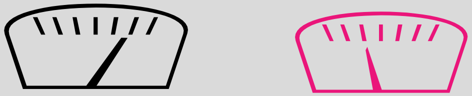


초전도 전자 소자
· 0.3 미크론 선폭 초전도 집적회로
· 300 GHz, 64bit 단자속양자 멀티플렉서
· 1Mbit CRAM
초전도 한류기
· 정격전압 : 154kV
· 정격전류 : 2000A
· 정격용량 : 533MVA
발전
부하
HTS Motor
초전도 변압기
· 정격용량 : 100MVA
· 1차전압 : 154kV
· 2차전압 : 22.9kV
초전도 케이블
· 정격전압 : 154kV(3상)
· 정격용량 : 1GVA
· 선로길이 : 200m
초전도 모터
· 정격효율 : 99%이상
· 무게 : 동급 50%이하
· 부피 : 동급 50%이하

전력기기를 초전도체로 만들면

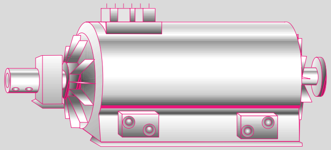


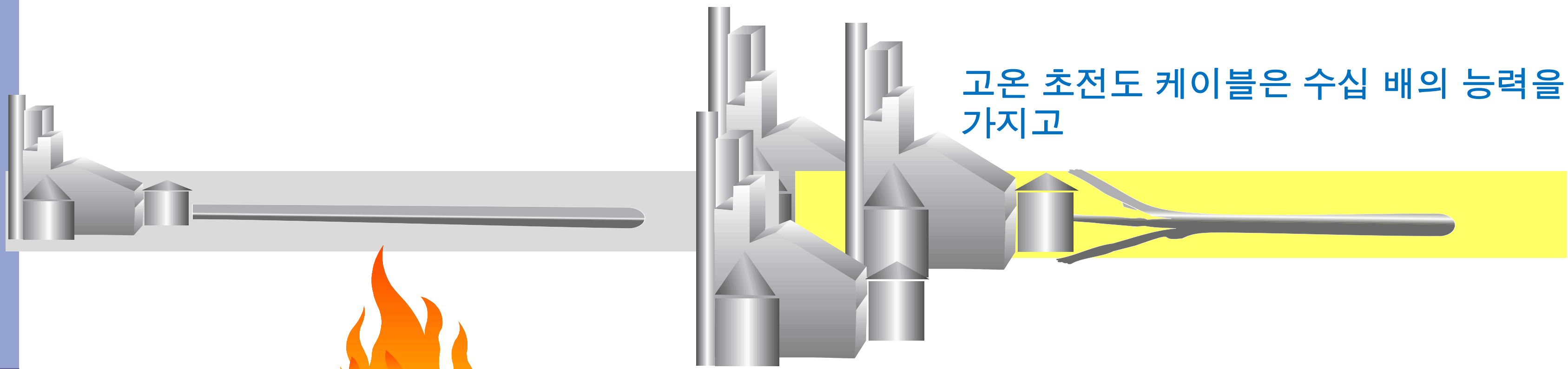




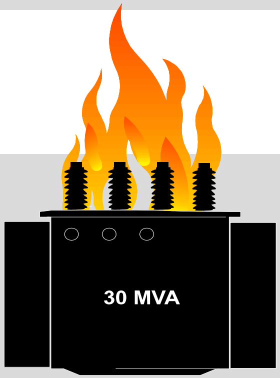
. . .전력 손실은 반밖에 안되고

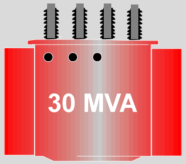
고온초전도 모터는 50% 작고 가벼우며



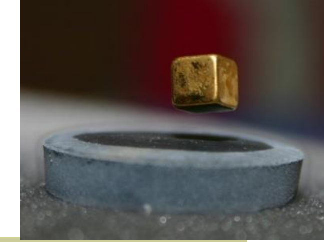


고온 초전도 케이블은 수십 배의 능력을 가지고

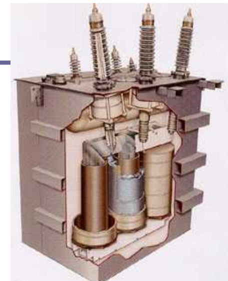


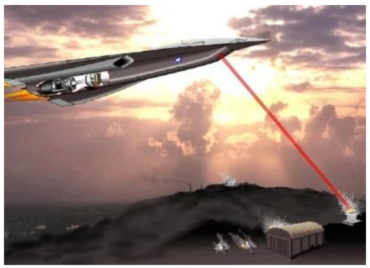


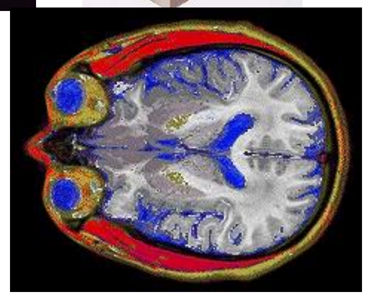
고온 초전도 변압기는 기름을 사용하지 않아 인화성이 없고 소음이 적다.

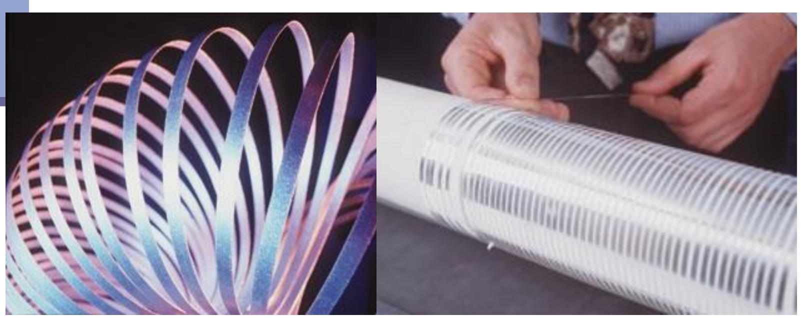


초전도 전력기기를 제작하려면



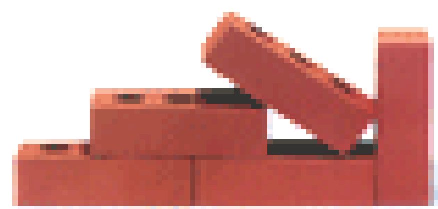






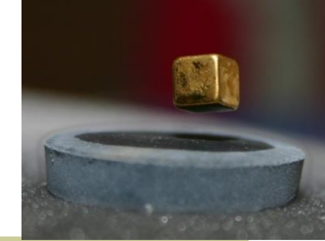
고온초전도 전선이
필요하다

벽돌집을 지으려면

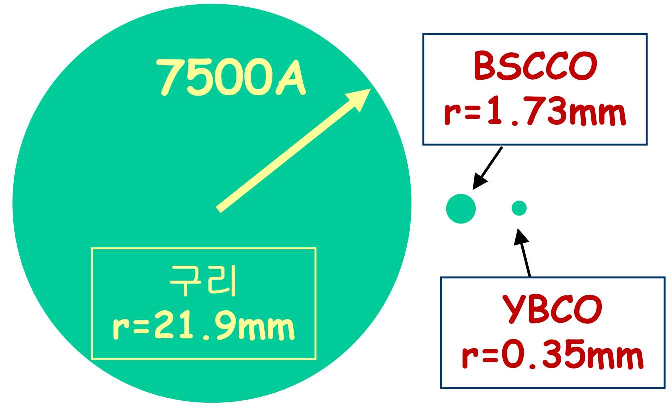


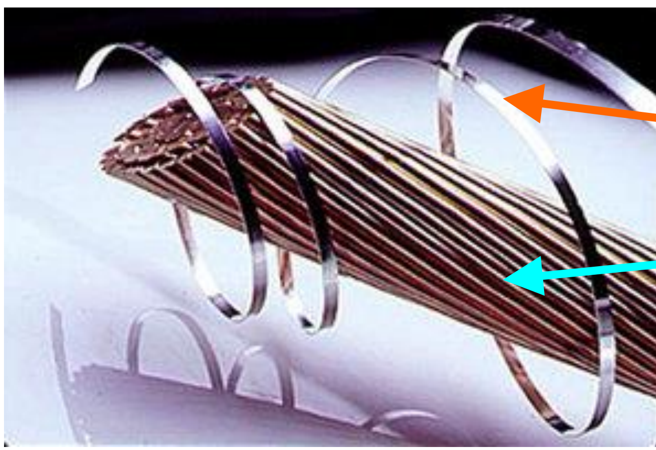
벽돌이 필요하고

초전도체로 전선을 만들면



액체 질소온도(77K)에서 7500 A 의 전류를 보낼 수 있는 도선의 반지름 비교





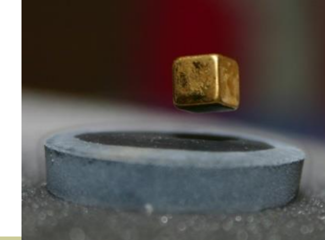
한 가닥의 고온 초전도 전선 (4mm x 0.2mm)

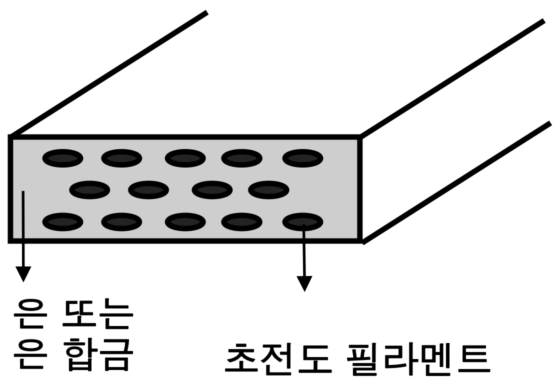
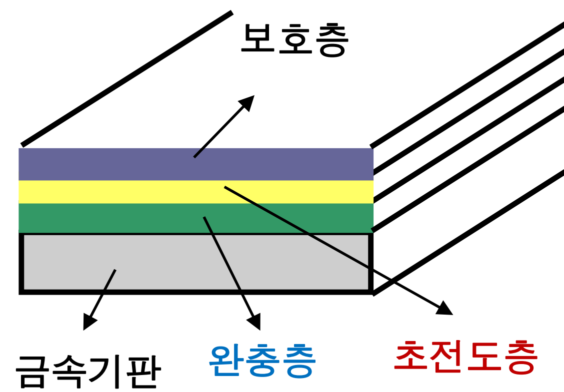
이 두꺼운 구리선 다발과 같은 양의 전류를

보낼 수 있다.

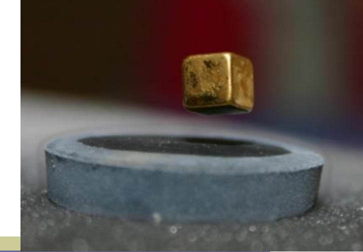
깨끗하고, 보다 효율적이고, 안전하고,
가볍고, 믿을 수 있고, 환경친화적이다.

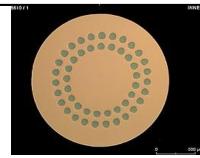
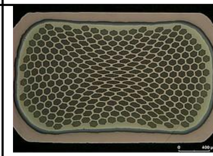
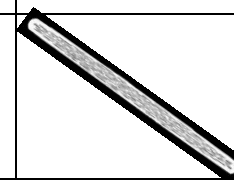
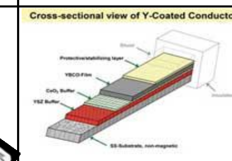
고온초전도 전선 제조 기술



	제 1 세대	제 2 세대
물질	BSCCO	YBCO
사용가능 온도	< 30 K	액체 질소 온도
개발 상황	상업화	상업화
구조		

현재 상용화 되고 있는 초전도 전선



	NbTi	Nb_3Sn	MgB_2	Bscco	YBCO
Wire type					
T_c (K)	9 K	18 K	39 K	108 K	90 K
B_{c2} (T)	10 T	28 T	<70 T	>100 T	>100 T
Operation in LN_2	NO	NO	NO	< 1T	<2T
Ductile compound	YES	NO	NO	NO	NO
Flexible wires	YES	NO	YES	YES	YES
Superconducting splices	YES	YES	YES	NO	NO
Low cost	YES	≈YES	YES	NO	Not yet

LTS (NbTi, Nb_3Sn) MTS (MgB_2) HTS (Bscco, YBCO)

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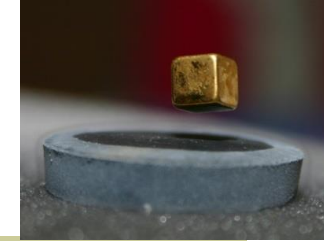
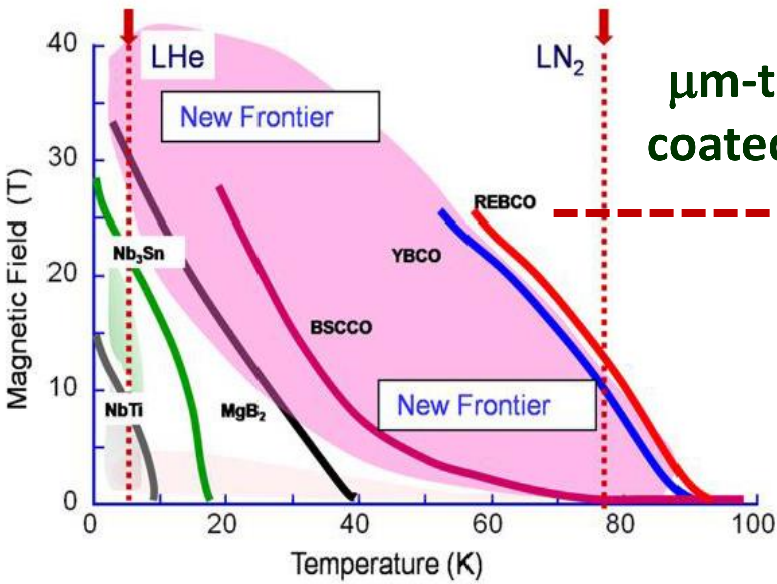
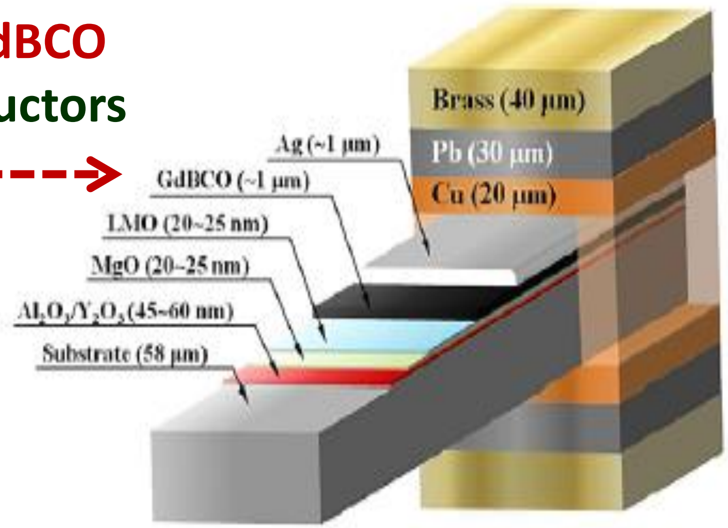
Power application of $REBa_2Cu_3O_{7-\delta}$





Matsumoto *et al, Supercond. Sci. Technol. 23 (2010) 014001*

μm-thick GdBCO coated conductors



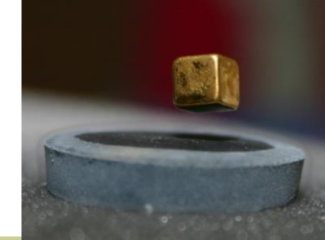
Choi *et al, Supercond. Sci. Technol. 25 (2012) 105001*

Superconductivity applications by using coated conductor (CC) technology

A schematic illustration of GdBCO CC tape manufactured by SuNAM Corp.

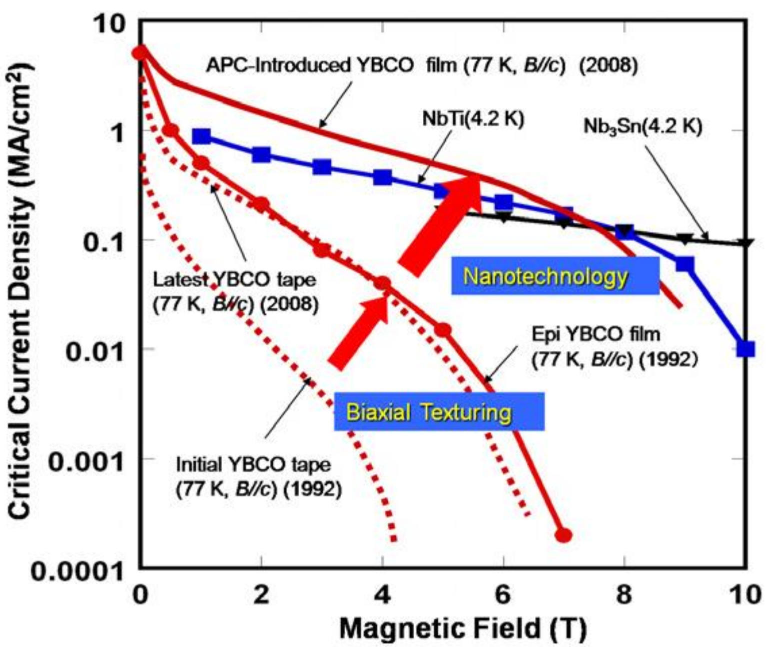
Power applications of CC require them to carry high critical current (I_c) in high magnetic field (H)

Issues need to be solved



➢ Field dependence of J_c

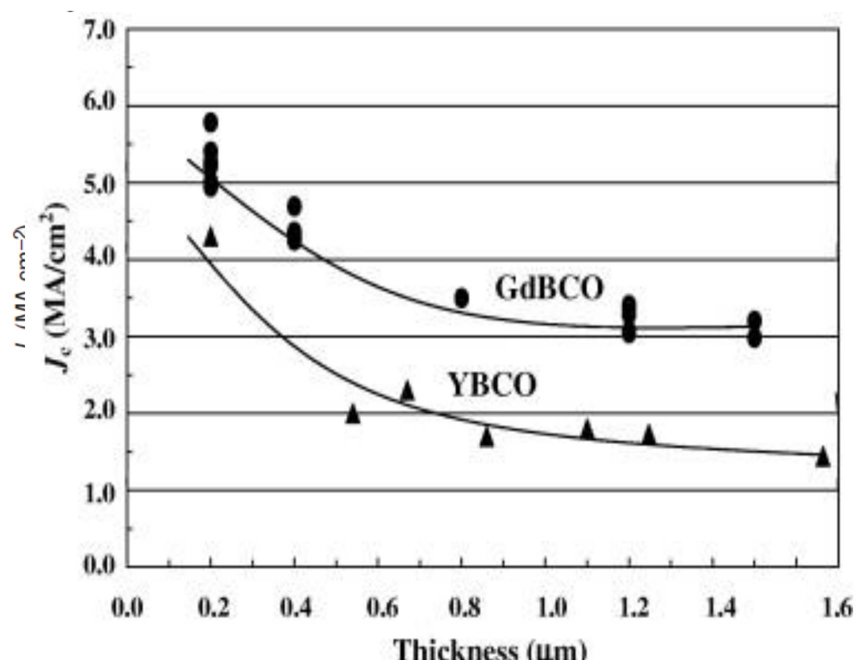
Matsumoto *et al, Supercond. Sci. Technol.* **23** (2010)



➢ Thickness dependence of J_c

a

Kinoshita *et al*, Physica C, **463** (2007)



"As the film is grown thicker current-blocking defects such as misoriented crystallites, cracks or voids become more prevalent".

Foltyn *et al*, Nature Materials (2007)

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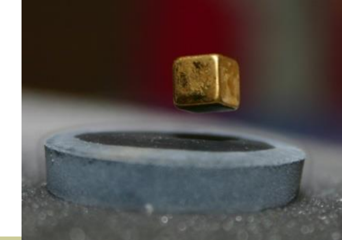
Flux-pinning in HTS

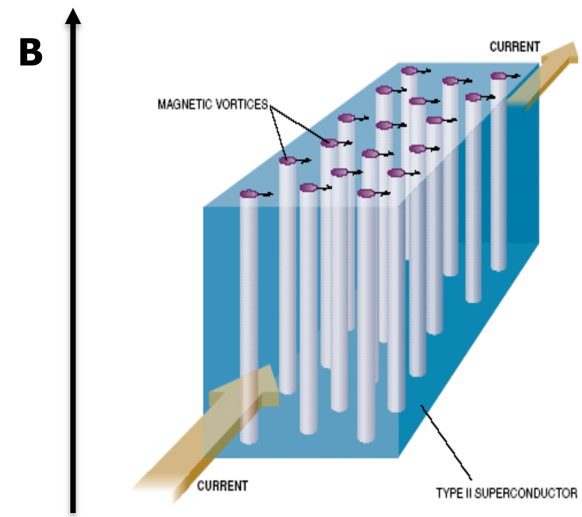


- **Importance of flux-pinning**

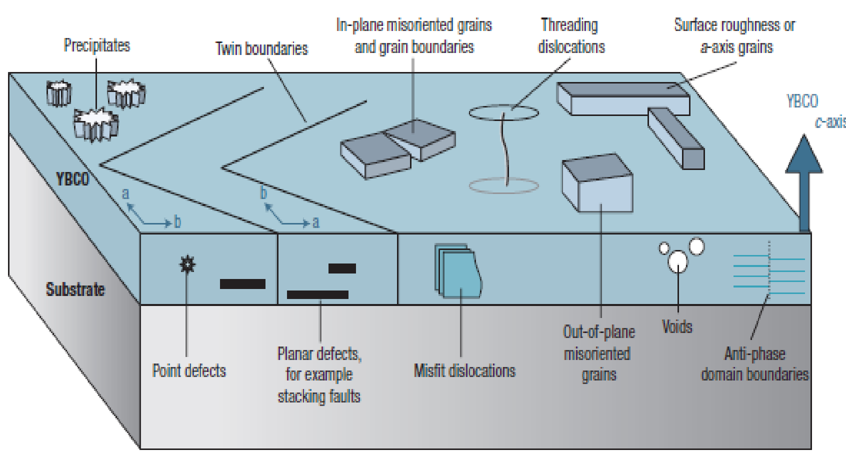
  Problem

  As current flowing
  - Lorentz forces act on vortices $F_L = J_{tr} \times B$
  - Vortices move and generate resistance

  Solution
  - Pinning of vortices by defect structures
  - Need $F_P > F_L$



- **Flux pinning by natural defects**



- **Additions of artificial defects ⇒ Enhancements of J_c**

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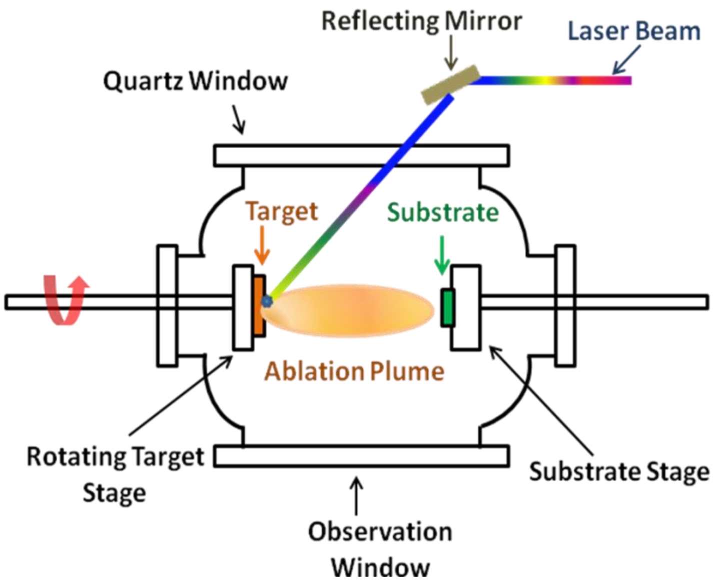
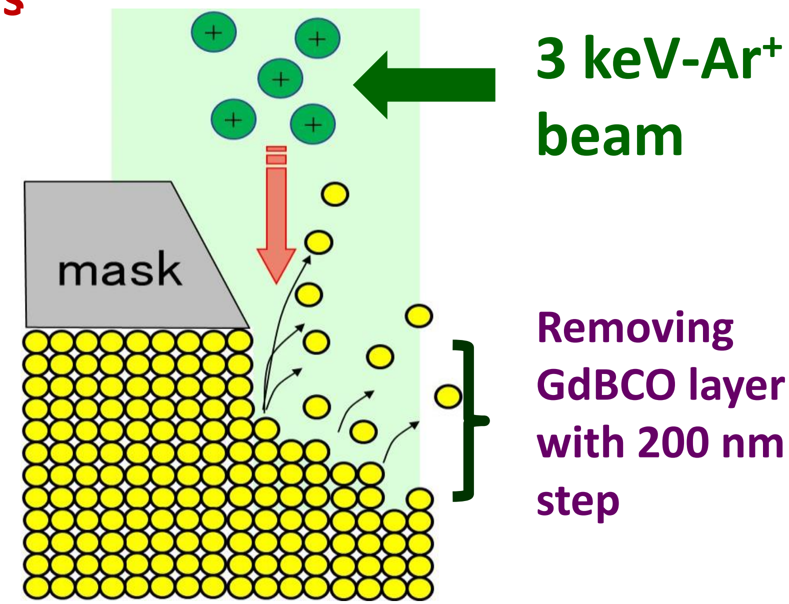
Experimental techniques

- **Fabrications of GdBCO films**



pulsed laser deposition system

- **Ar^{+} ion-milling on μm-thick GdBCO films**



- GdBCO film with and without addition of BSO
- GdBCO films with varying thickness up to 1.5 μm
- Surface SEM of GdBCO films with residual film thickness
- Microstructural evolution inside the GdBCO films

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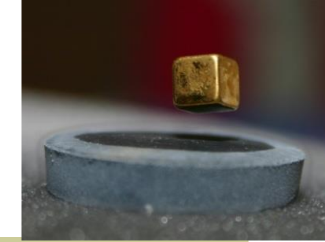
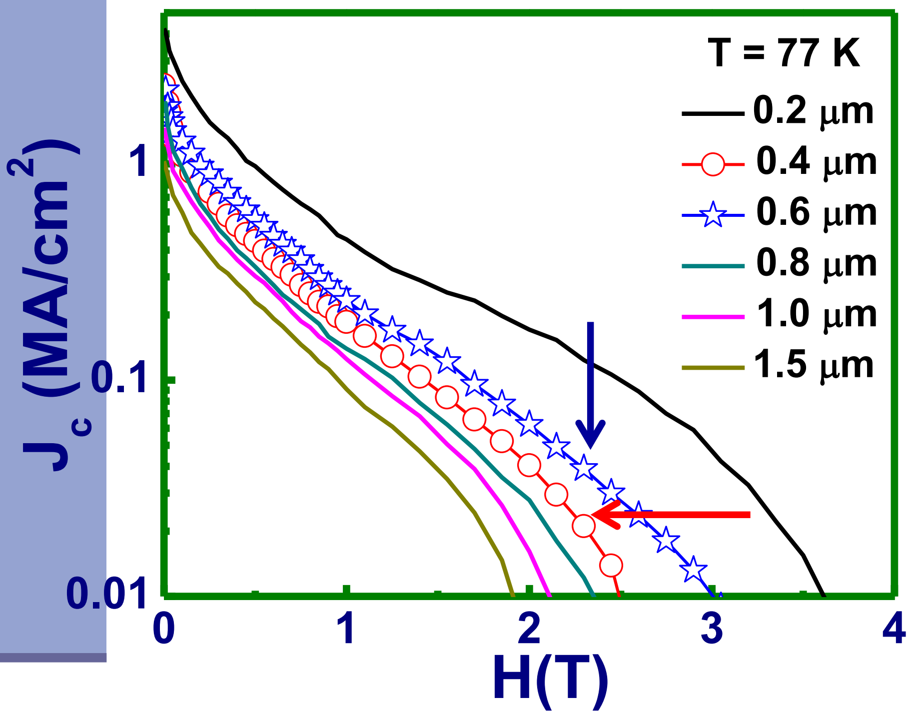
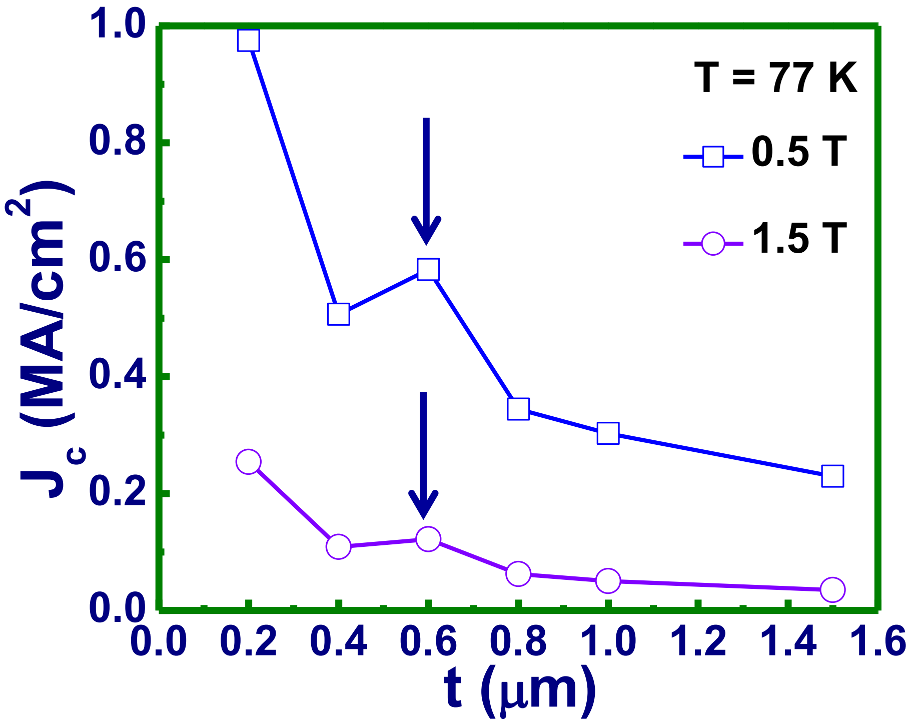
J_c of GdBCO films



- **Field dependence of J_c**



- **Thickness dependence of in-field J_c**



- **In-field J_c decreases with film thickness**
- **An inversion of J_c occurred at *t* ~ 0.6 μm**
- **A peak is observed in the J_c-t behavior at *t* ~ 0.6 μm**

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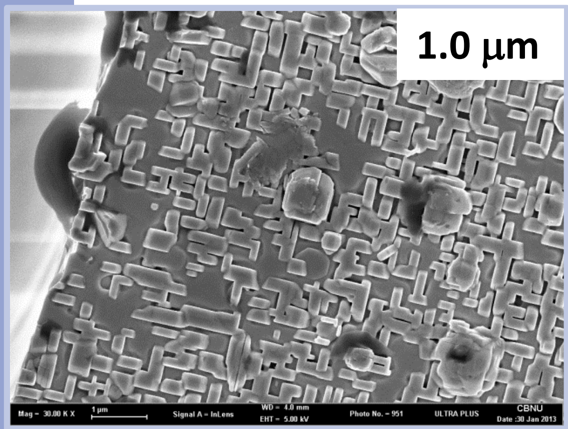
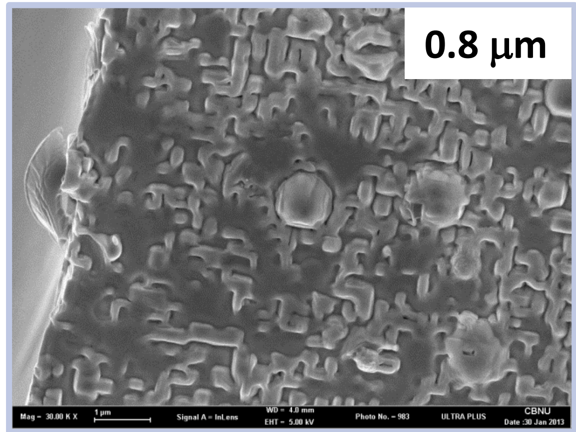
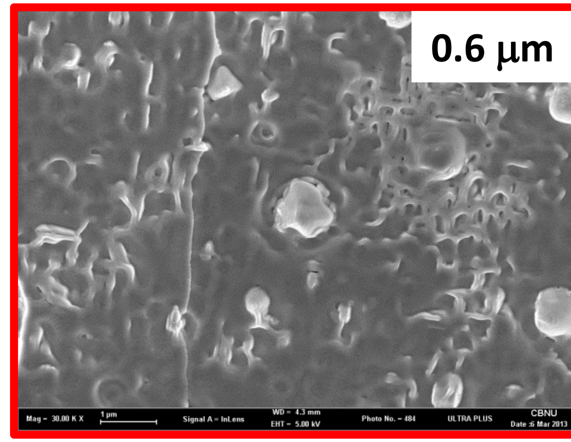
Microstructural evolution in GdBCO films

➢ Surface morphology after ion-milling

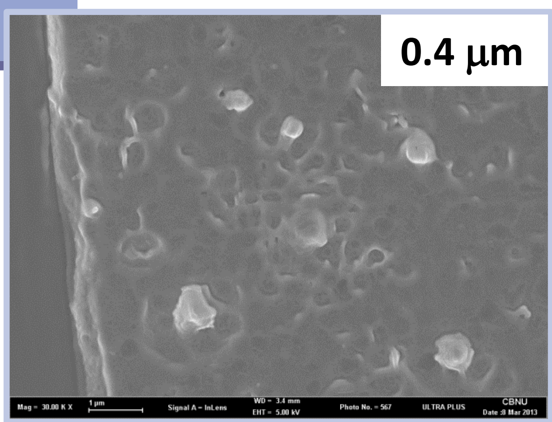


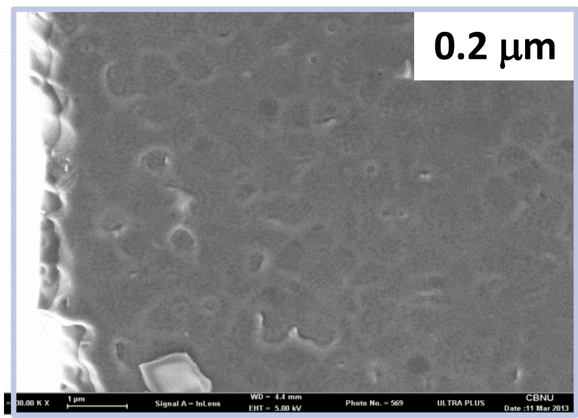




Thicker GdBCO films ⇒ lower surface temperature

⇒ Development of *a*-axis oriented grains





$t \sim 0.6$ μm

- **a-axis grains start to grow**
- **Pores with size < 40 nm form at intersections of perpendicularly connected grains**

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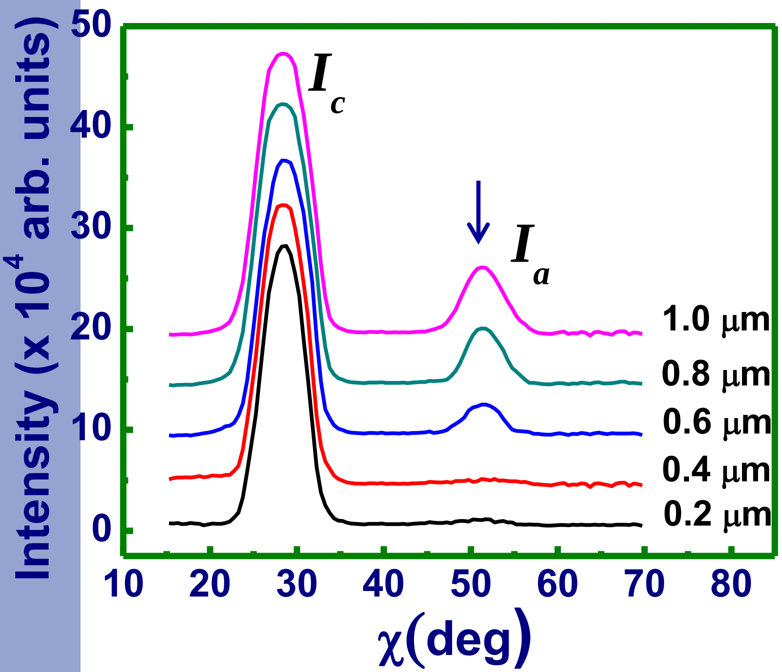
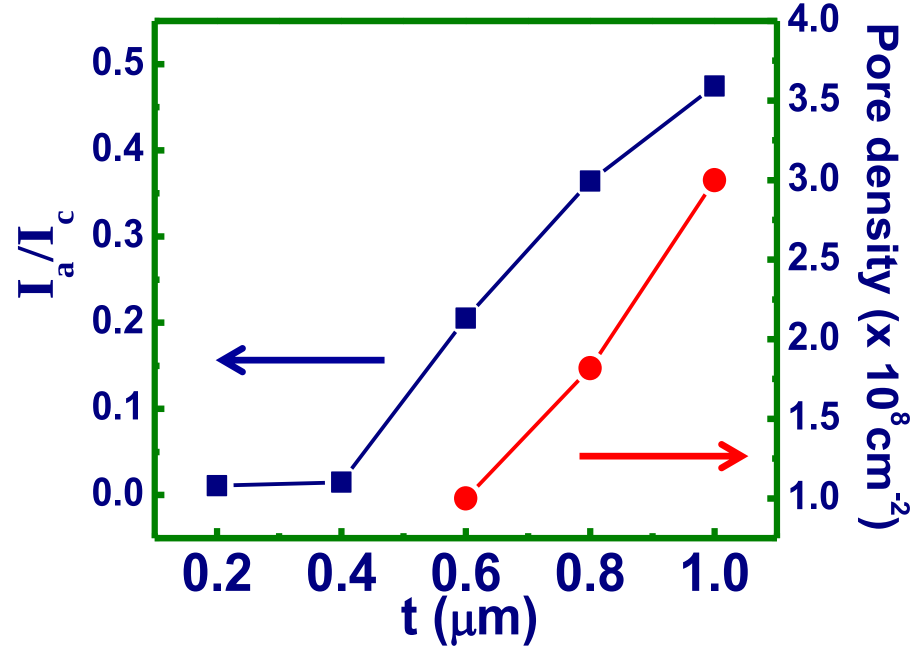
Qualitative analysis





Increasing the residual film thickness t

- **Lower surface temperatures**
- **Remarkable development of the *a*-axis grains**
- **Increase in the formation of nanopores**

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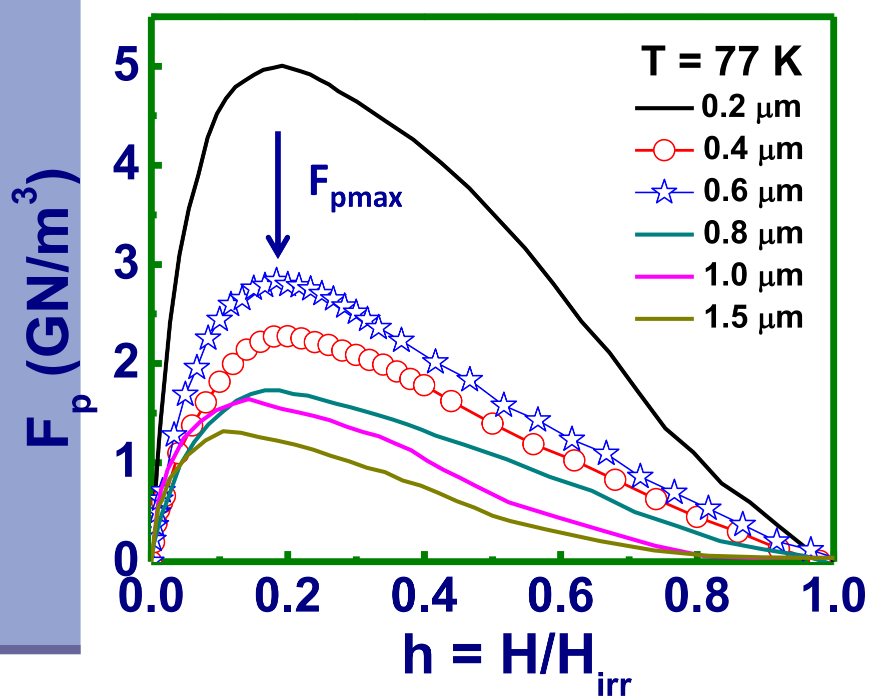
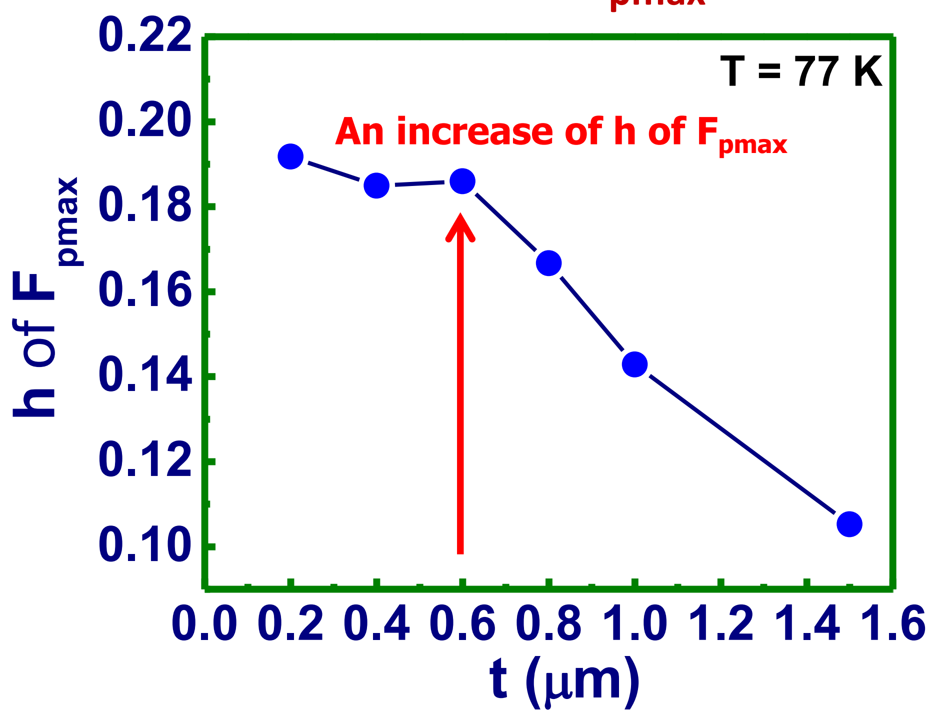
Intrinsic pinning property of GdBCO

- Pinning force F_p versus t

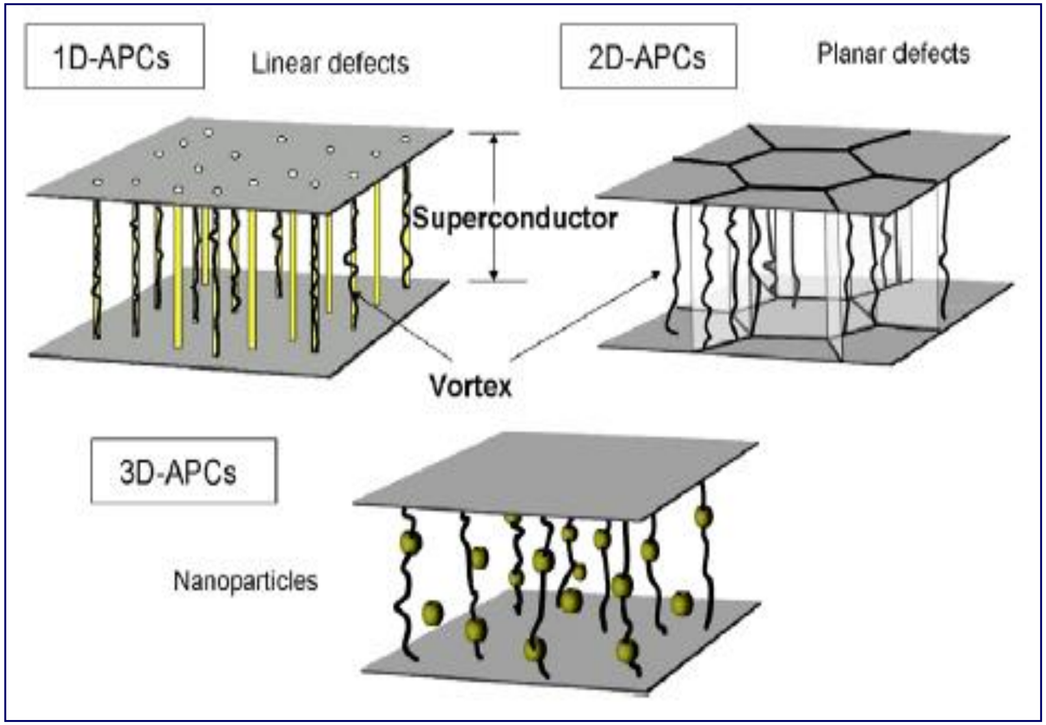


- Position of F_{pmax}



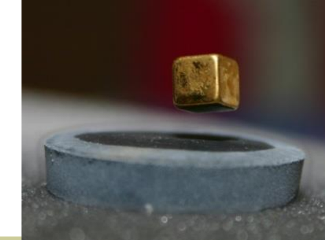
- F_p at *t* ~ 0.6 μm > F_p at *t* ~ 0.4 μm
- Shifts of F_{pmax} to lower/higher h ⇒ Less/more effective pinning
- **Nanopores:** effective pinning centers
- Strong current blocking by a-axis grains at thick films

Artificial Pinning Centers in HTS



- **1D-APCs:**
  nanorods, columnar defects
- **2D-APCs:**
  grain boundaries,
  surfaces of large precipitates
- **3D-APCs:**
  nanoparticles,
  second phases of ξ scale

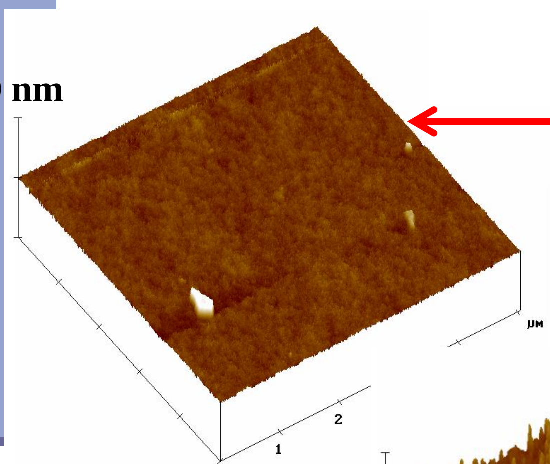
Growth of $BaSnO_3$ defects



- $BaSnO_3$ (BSO): Barium-based perovskite structure, self-assembling property

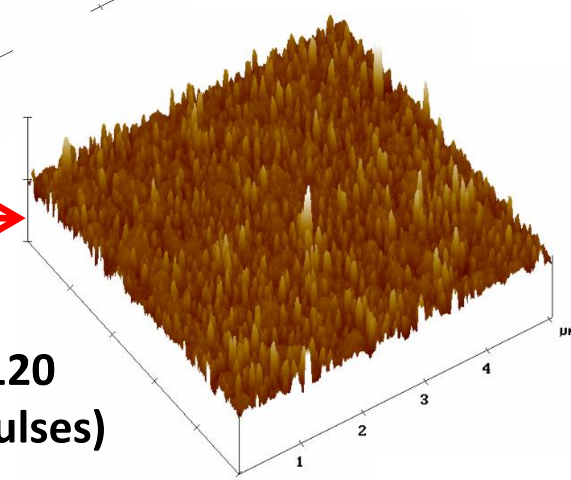
BSO nanoparticles (3D)

Separated targets of BSO and GdBCO



GdBCO buffer layer

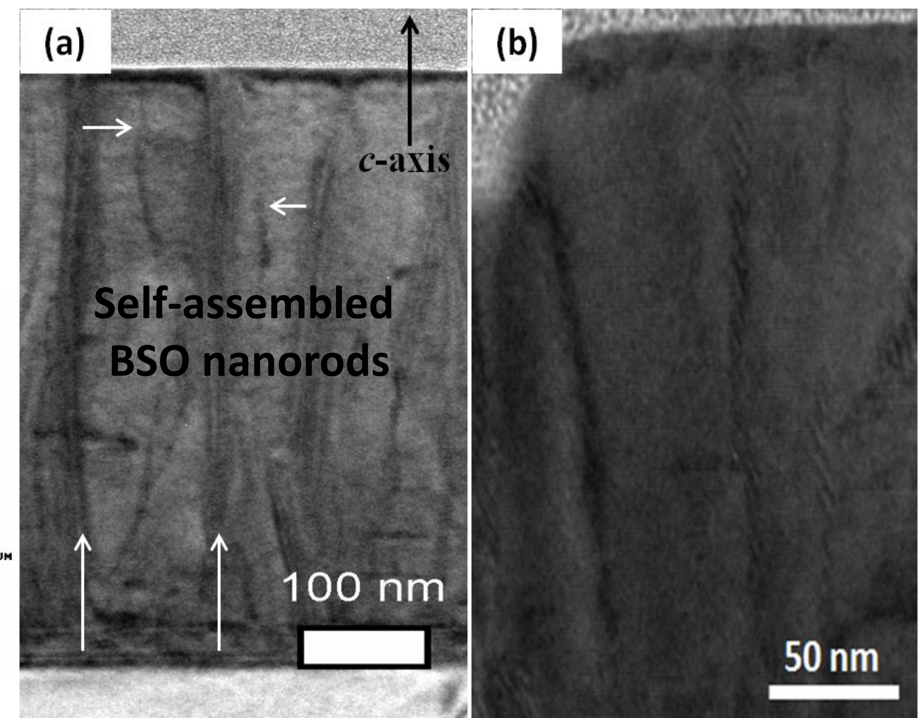
BSO nanoparticles



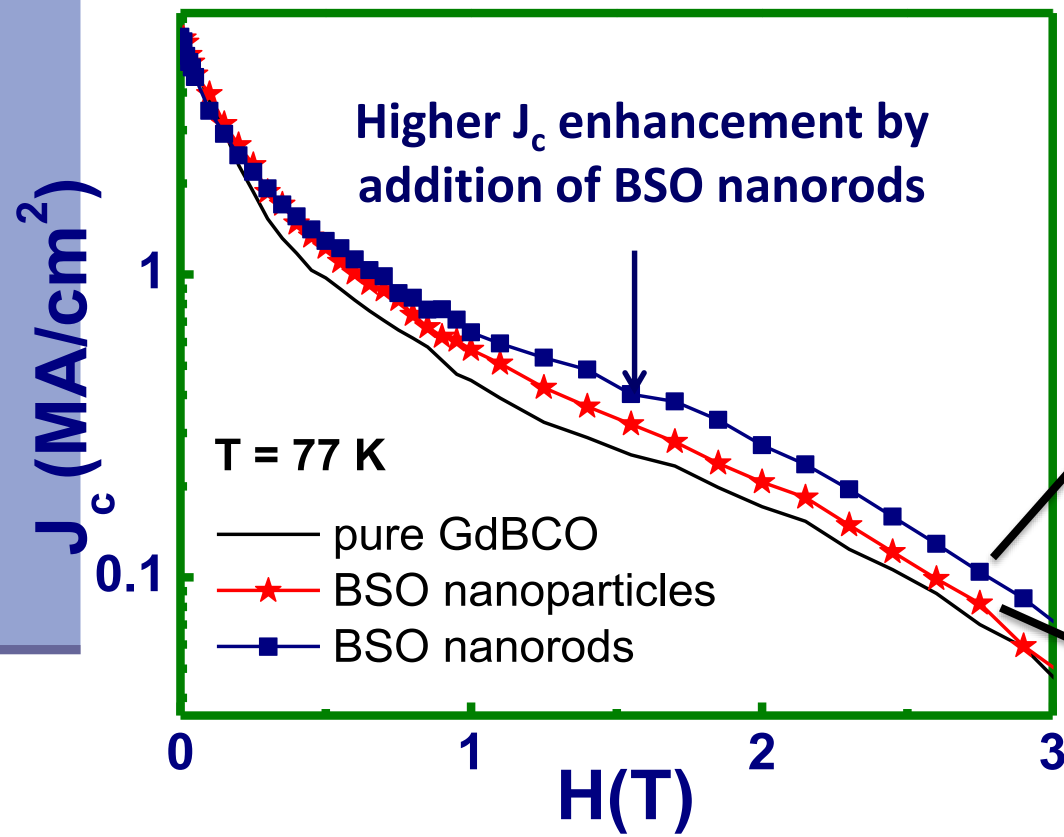
Laser pulses: 10-120
(AFM image of 40 pulses)

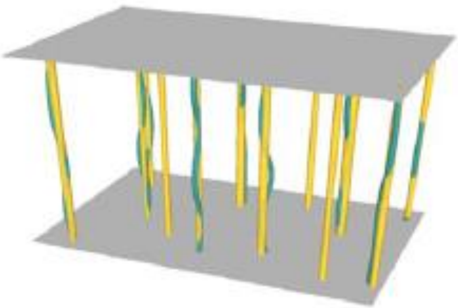
BSO nanorods (1D)

2 wt. % BSO-doped GdBCO target

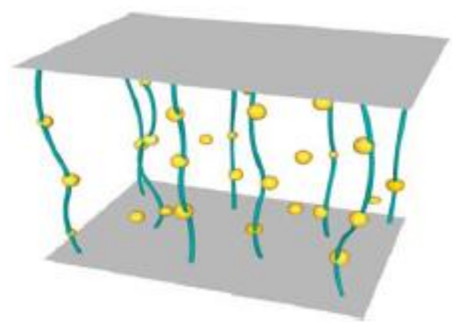


Comparison of 1D and 3D defects



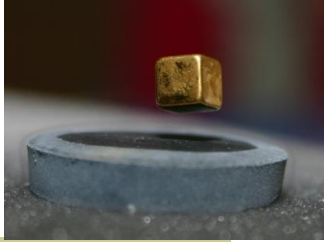


Pinning by 1D defects

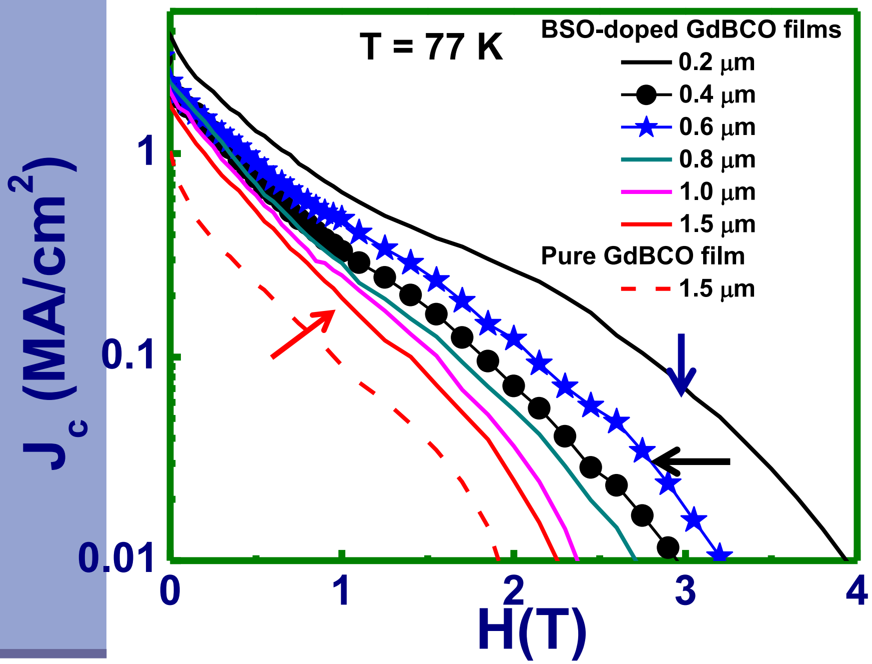


Pinning by 3D defects

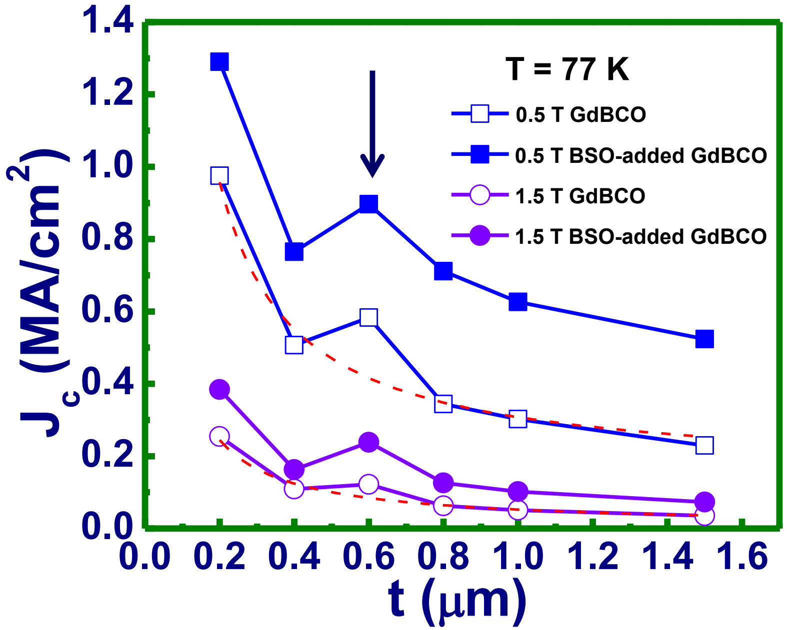
J_c of BSO-added GdBCO films



➢ Field dependence of J_c

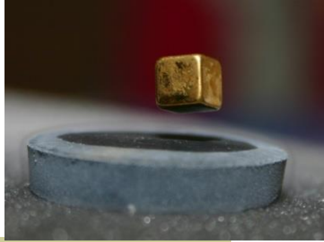


➢ Thickness dependence of in-field J_c

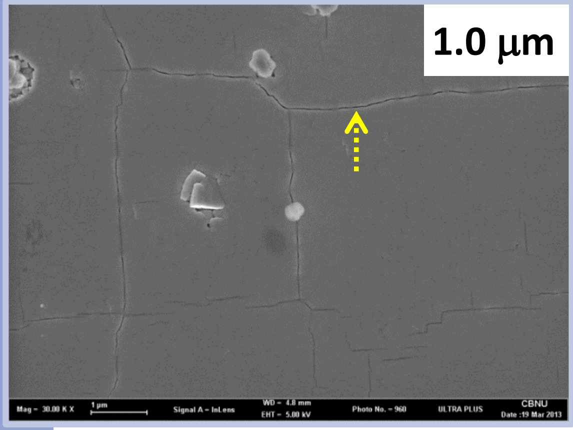


- J_c increases in BSO-added GdBCO film up to 1.5 μm-thick
- An inversion of J_c occurred again at *t* ~ 0.6 μm
- Strong pinning via BSO nanorods ⇒ invalidation of the collective pinning theory
- A peak at *t* ~ 0.6 μm might be related to evolution of BSO defects

Evolution of BSO defects



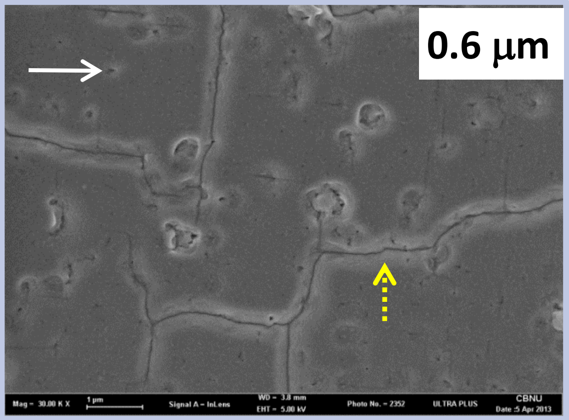
➤ Surface morphology after ion-milling

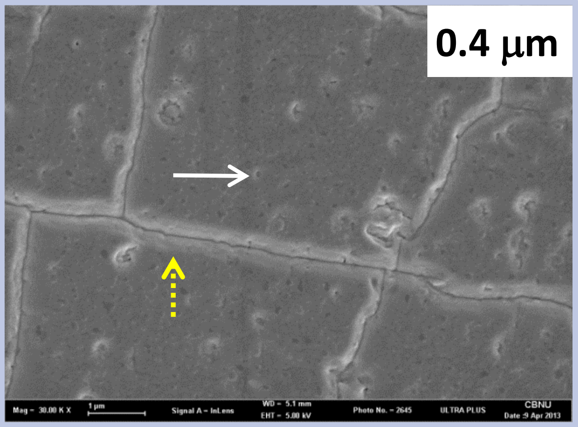


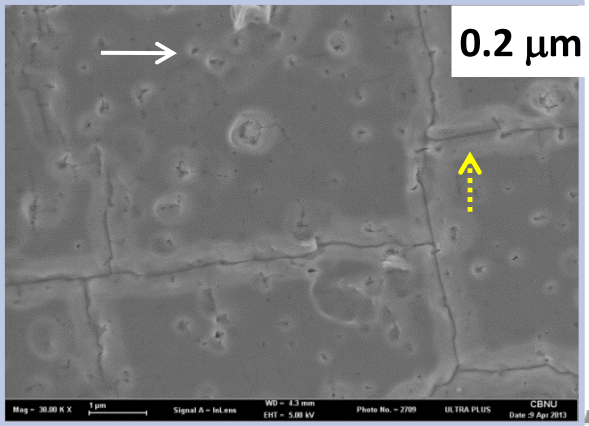
- New types of nanostructures :
  Pore & meandering grain boundary

- Distribution of meandering grain boundary does not depend on film thickness

- *a*-axis grains are significantly reduced in thick films







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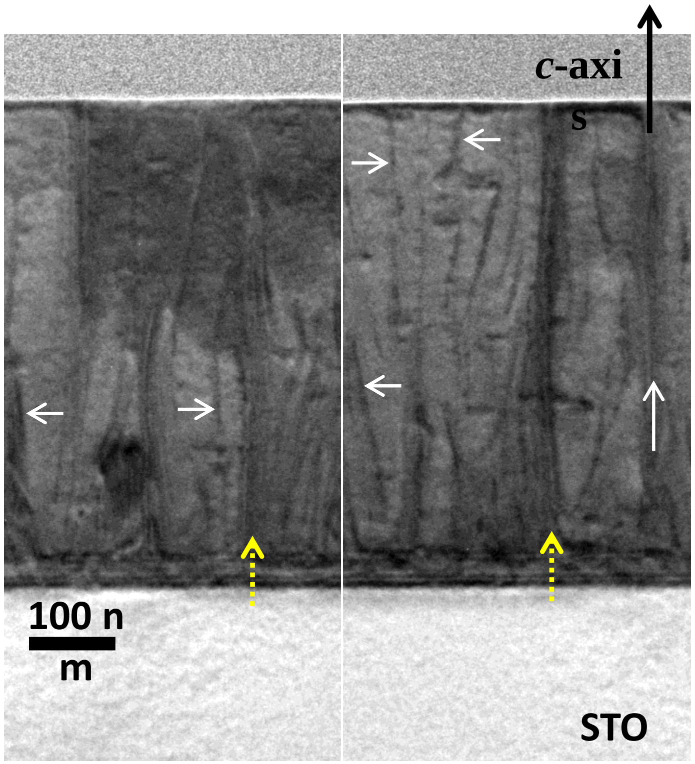
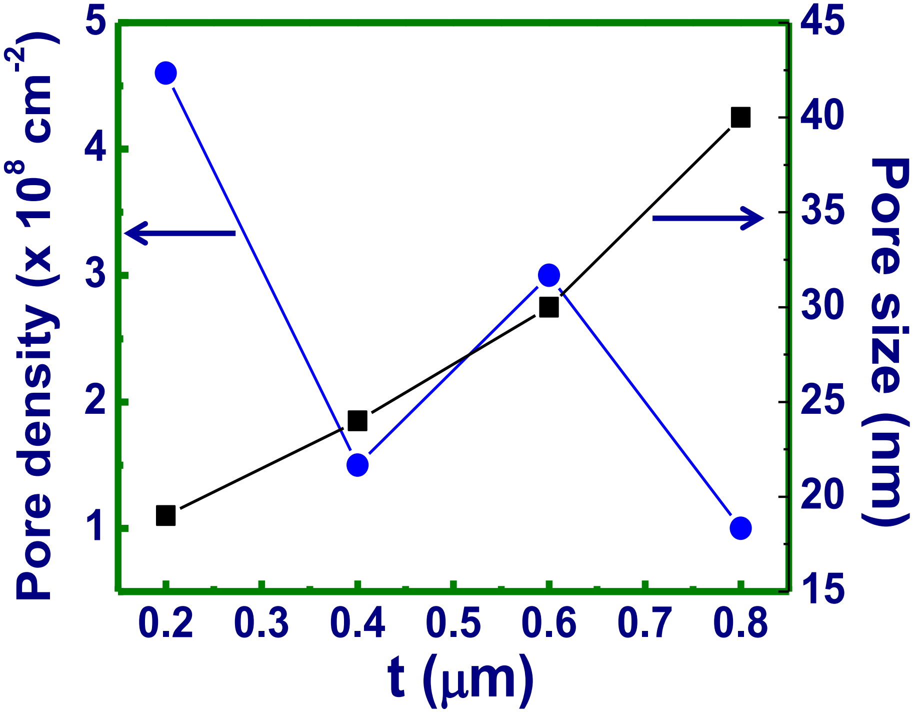
Qualitative analysis of BSO defects



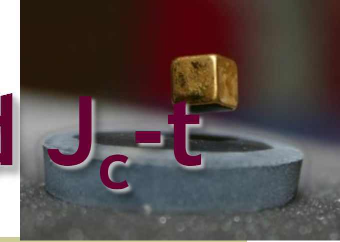
TEM image of 0.6 μm-thick BSO-added GdBCO films

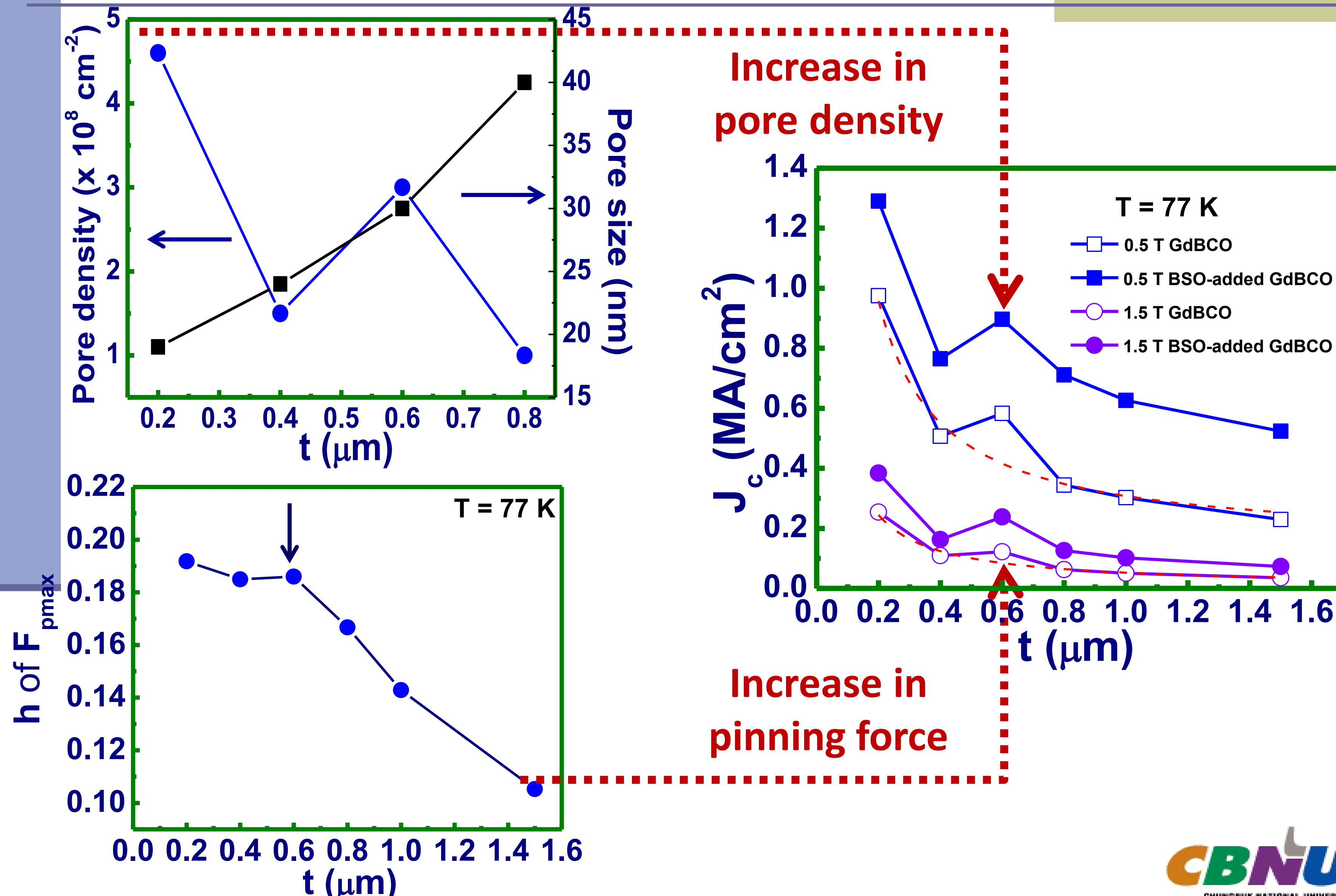


- Segments of BSO nanorods/nanopores
- Meandering grain boundaries are extended to the surface of film

- Size of nanopores increases with thickness
- Nanopores open and close at certain *t*
  ⇒ variation of the pore density versus *t*

Correlation of defects & in-field J_c-t





Summary

➢ Pure GdBCO

- Uncorrelated pinning in thin & thick film regions
- Correlated pinning in 0.6 μm-thick film

➢ BSO-added GdBCO

- Two types of nanostructure formed: nanorod & meandering grain boundary
- Both field dependence and thickness dependence of J_c are reduced by BSO addition
- Strongly correlated pinning through whole thickness range due to the formation of meandering grain boundary