

Workshop
“Neueste Entwicklungen auf dem Gebiet der LT/HT-Supraleiter”

Fe-basierte Supraleiter

Eigenschaften, Herstellung und Anwendungsperspektiven

Dr. Ruben Hühne

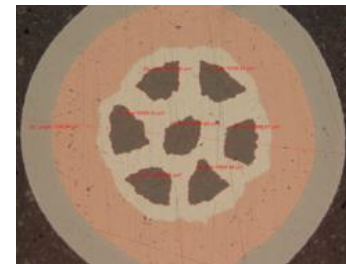
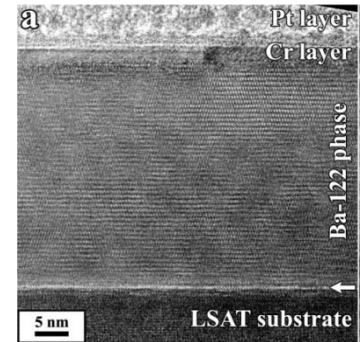
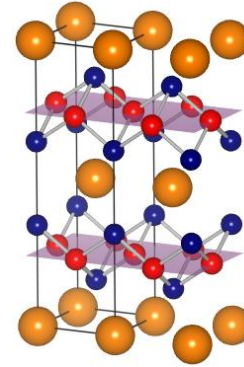
Funktionale Oxidschichten und Supraleiter

Institut für Metallische Werkstoffe

IFW Dresden

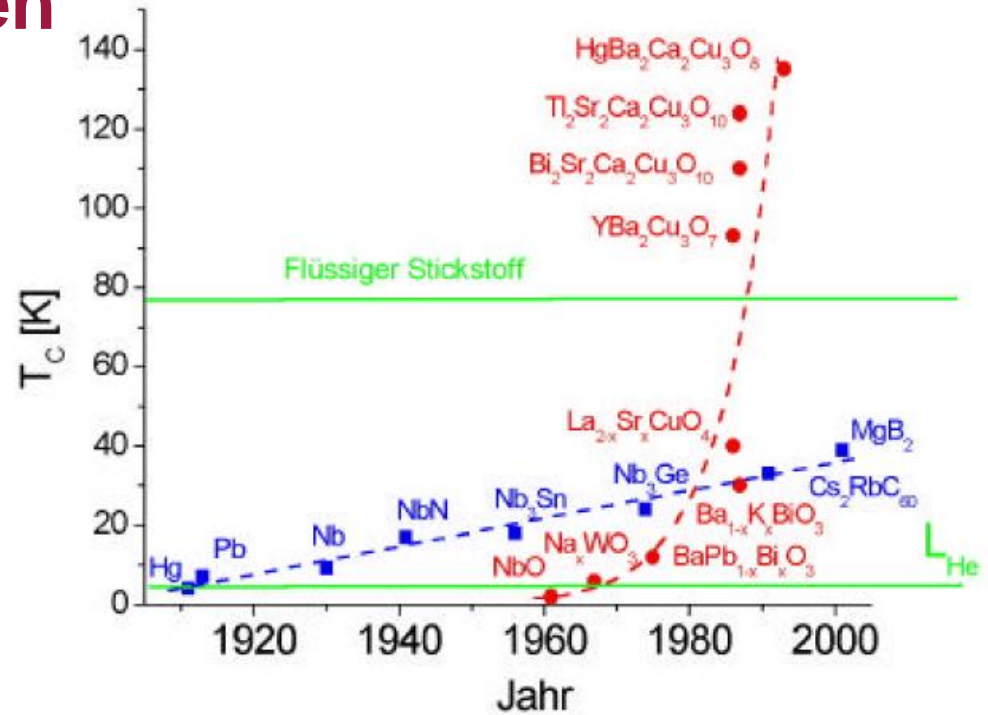
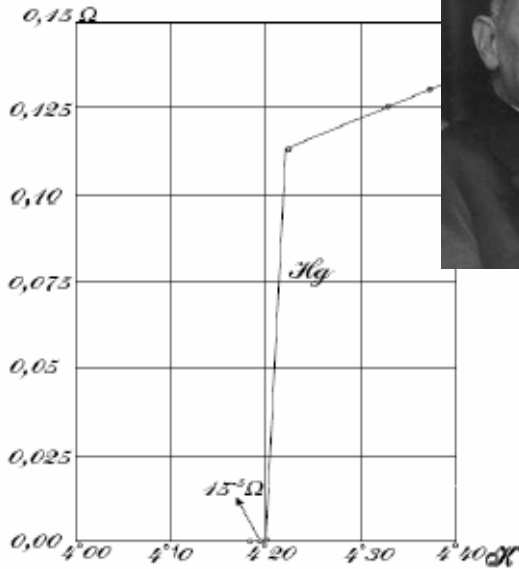
Inhalt

- Grundlegende Eigenschaften
 - Materialien
 - Phasendiagramm
 - Verhalten im Magnetfeld
 - Stromtragfähigkeit
- Herstellung von Leitermaterialien
 - Dünnschichtherstellung
 - PIT Technologie
- Anwendungsperspektiven



Supraleitende Materialien

H. Kamerlingh Onnes,
Leiden (1911)



Matthias' Regeln für hohes T_c (~1960)

- Hohe Symmetry
- Hohe Zustandsdichte bei E_F
- Kein Sauerstoff
- Kein Magnetismus → Kein Eisen!
- Keine Isolatoren



Bernd T. Matthias

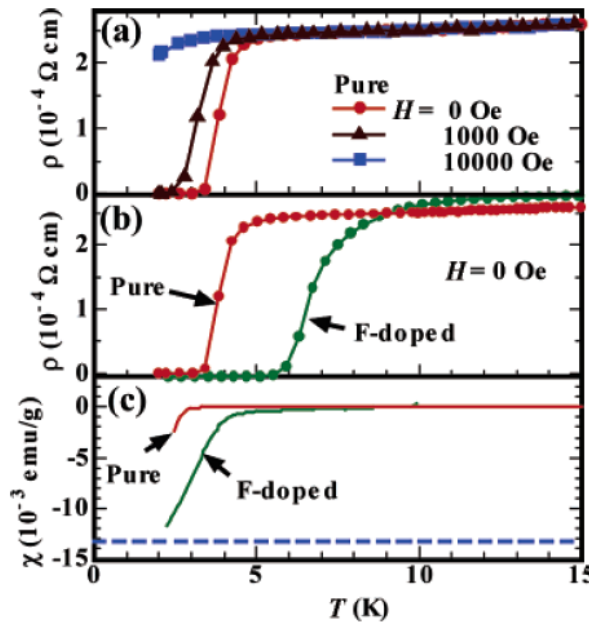
Entdeckung Fe-basierter Supraleiter



Gruppe von Prof. Hideo Hosono (Tokyo Institute of Technology)

Schwerpunkt der Arbeiten: transparente / magnetische Halbleiter

LaOFeP

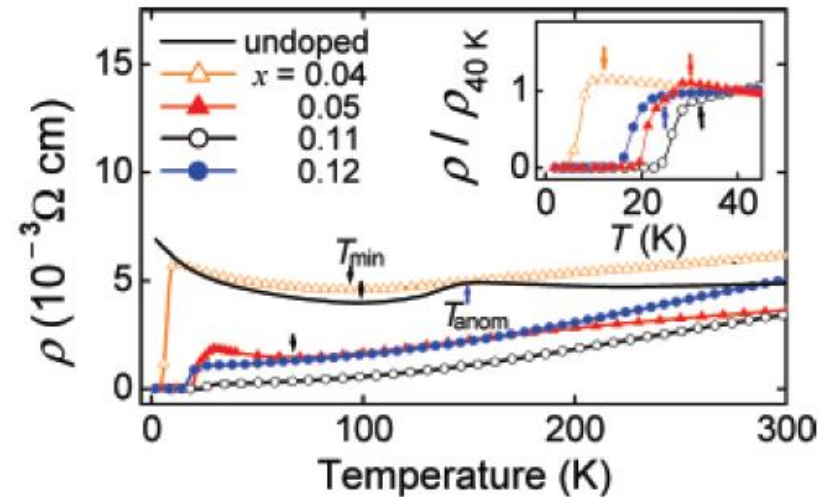


Y. Kamihara et al., J. Am. Chem. Soc. 128 (2006) 10012

$T_c \sim 4$ K

→ Neuer „Goldrausch“ in der Supraleiterforschung

La(O_{1-x}F_x)FeAs

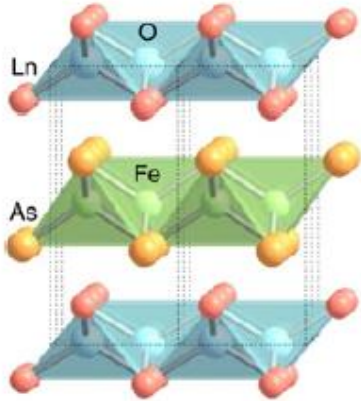


Y. Kamihara et al., J. Am. Chem. Soc. 130 (2008) 3296

$T_c \sim 26$ K

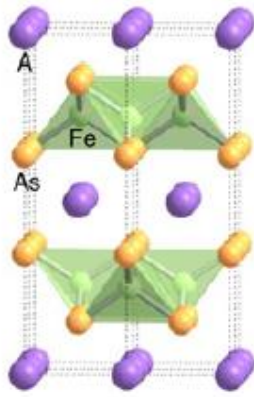
Fe-basierte Supraleiter

1111



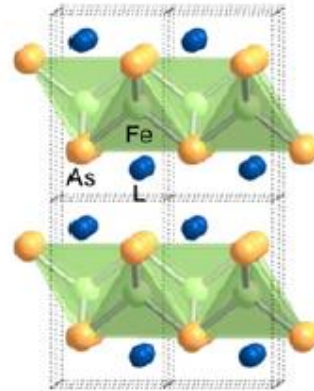
(a) LnFeAsO
(Ln = rare-earth).

122



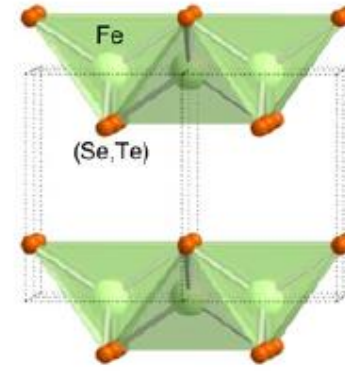
(b) AFe_2As_2 (A = Ca, Sr, Ba).

111



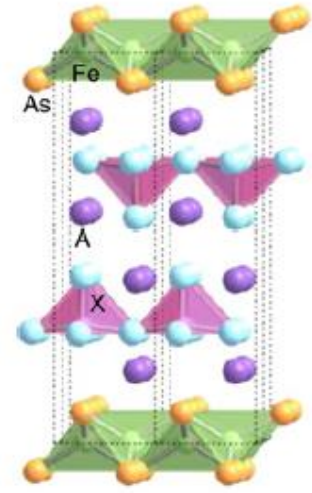
(c) LFeAs (L = Li, Na).

11



(d) $\text{Fe}(\text{Se}, \text{Te})$.

21113



(e) $\text{A}_4\text{X}_2\text{O}_6\text{Fe}_2\text{As}_2$
(A = Ca, Sr) (X = Mg, Al, Sc, Ti, V, Cr).

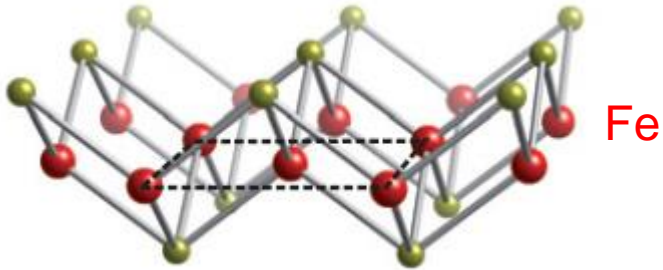
- Riesige Vielfalt an Verbindungen
- Sprungtemperaturen bis 56 K (Sm1111)
- Monolage FeSe on SrTiO_3 : ~110 K
- Lagenartige Kristallstruktur, gemeinsames Element: Fe Pn - bzw. Fe Ch -Lagen

Lee et al., Solid State Communications 152 (2012) 644–648

Wang, Hosono, Dai (ed.) Iron Based Superconductors, CRC Press, 2013

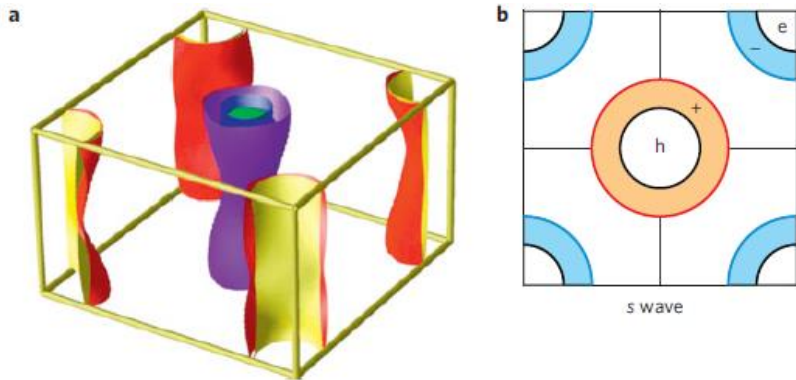
Fe-basierte Supraleiter

Supraleitung in FePn/FeCh-Ebenen



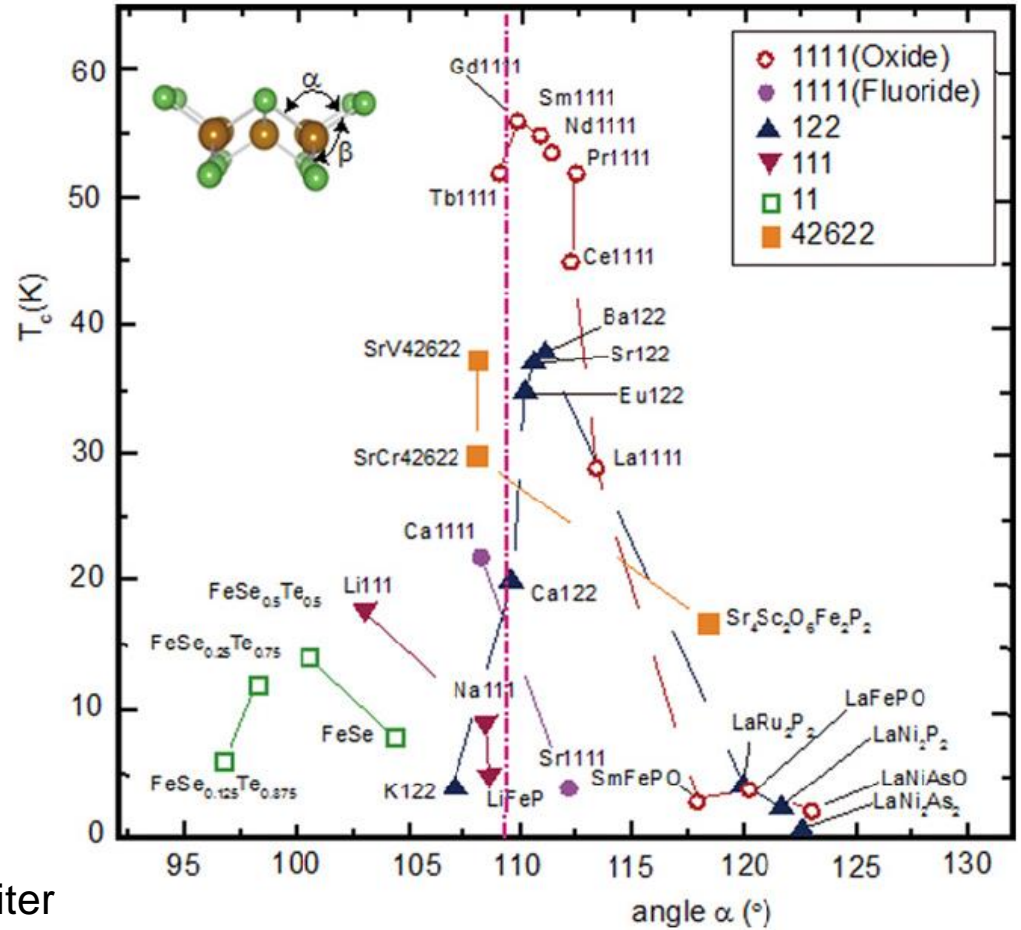
Pniktide: Fe-As- or Fe-P Lagen

Chalkogenide: Fe-Se- or Fe-(Se,Te) Lagen



Komplexe Fermiflächen: Mehrbandsupraleiter

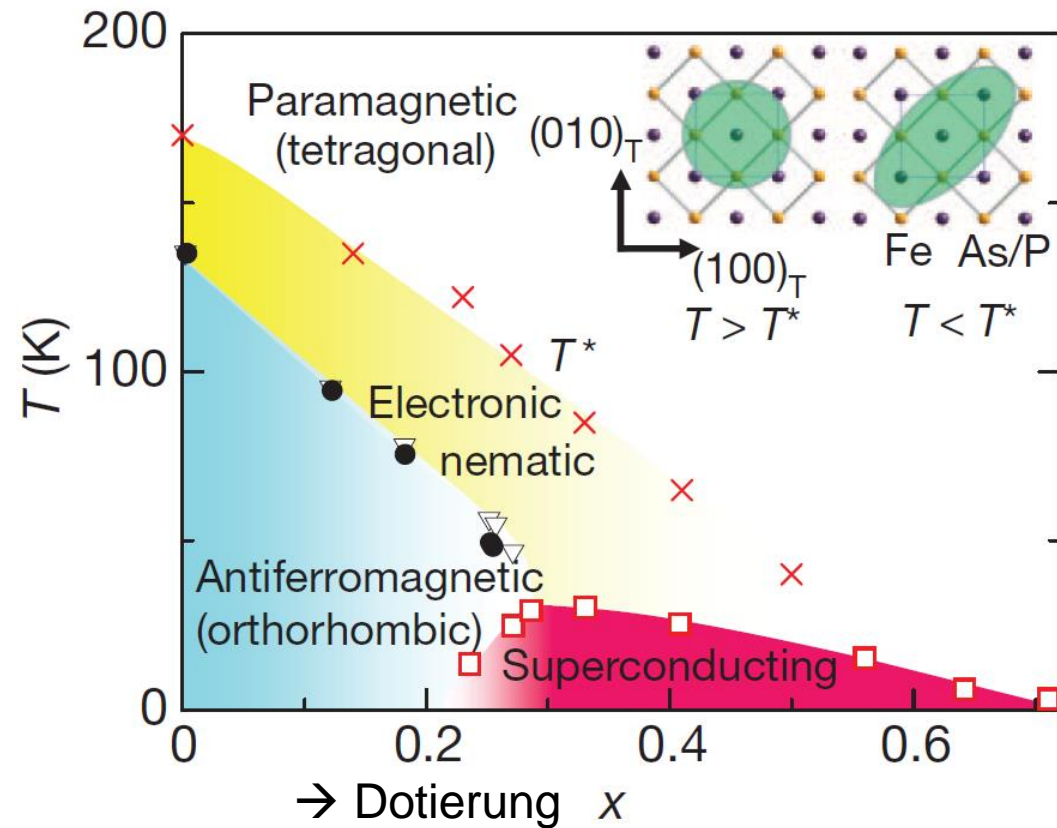
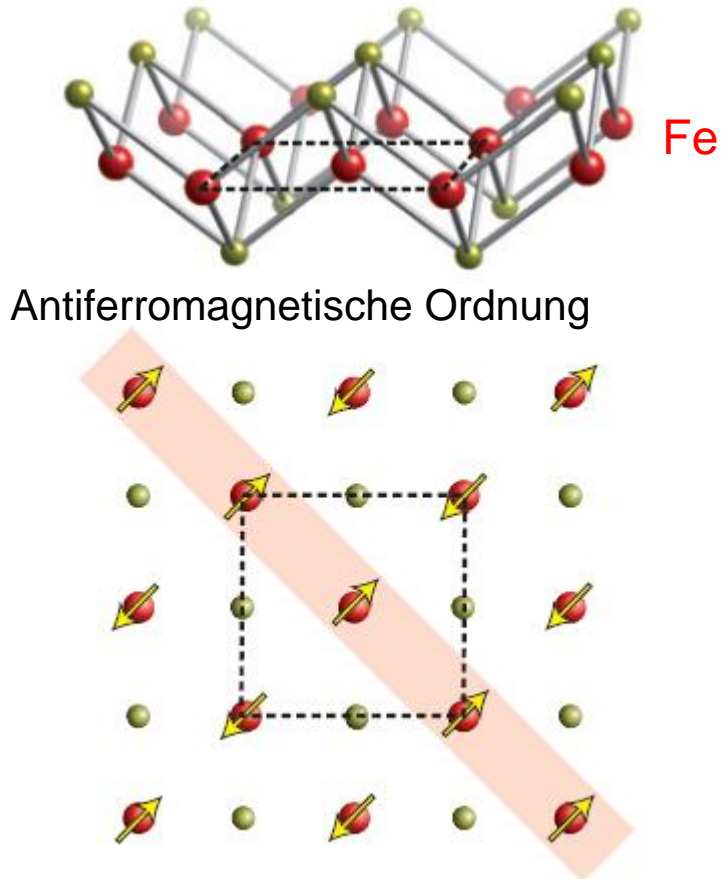
J. Paglione et al., Nat. Physics 6 (2010) 645



H. Hosono et al., Sci. Technol. Adv. Mater. 16 (2015) 033503

Phasendiagramm Fe-basierte Supraleiter

Supraleitung in FePn/FeCh-Ebenen Phasendiagramm $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$

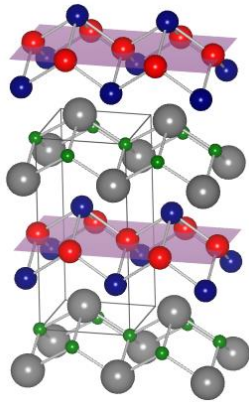


J. Paglione et al., Nat. Physics 6 (2010) 645

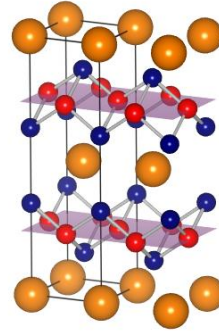
S. Kasahara et al., Nature 486 (2012) 382

Phasendiagramm Fe-basierte Supraleiter

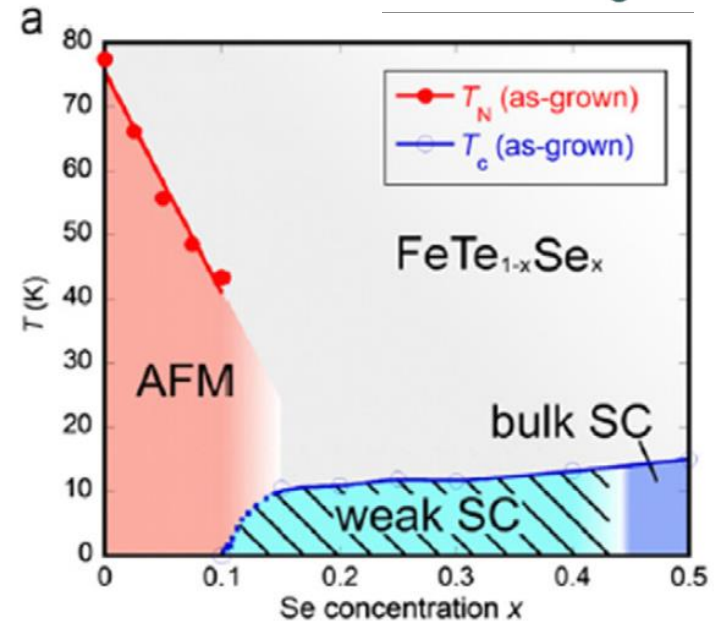
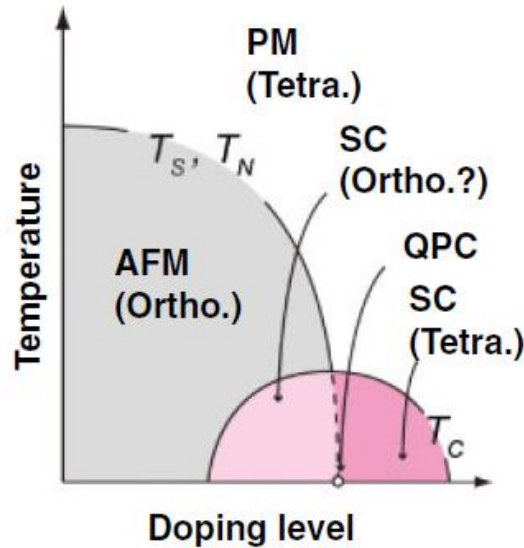
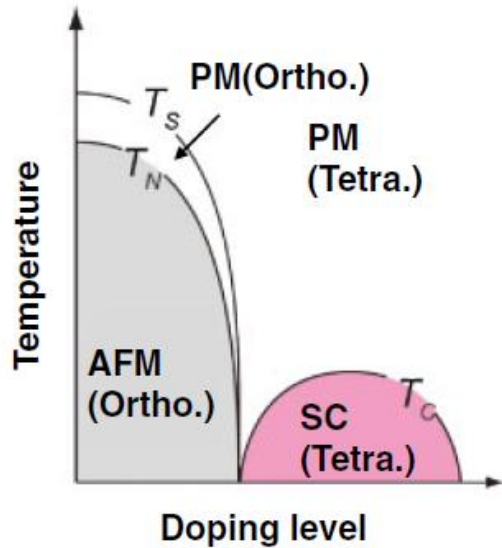
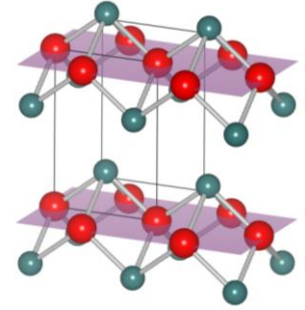
1111



122



11

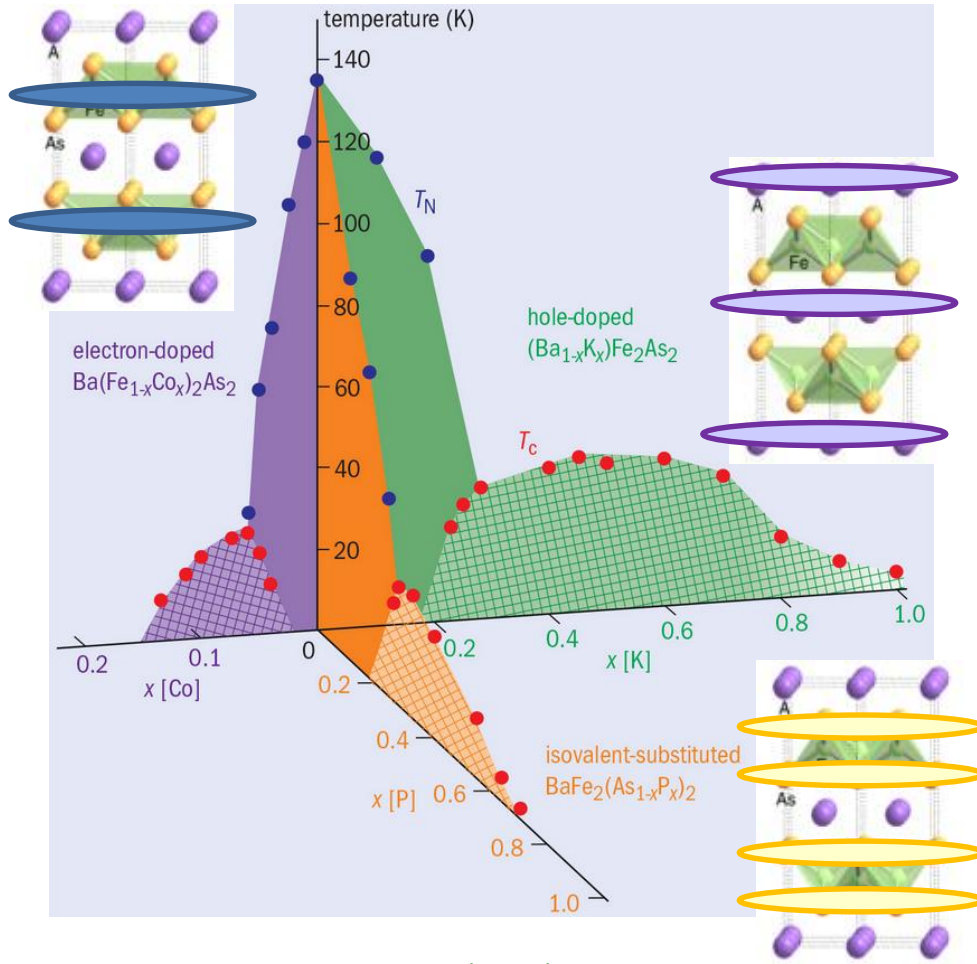


H. Hosono, in: "100 Years of Superconductivity", CRC Press (2012) 255

K. Deguchi et al., Sci. Technol. Adv. Mater. 13 (2012) 054303

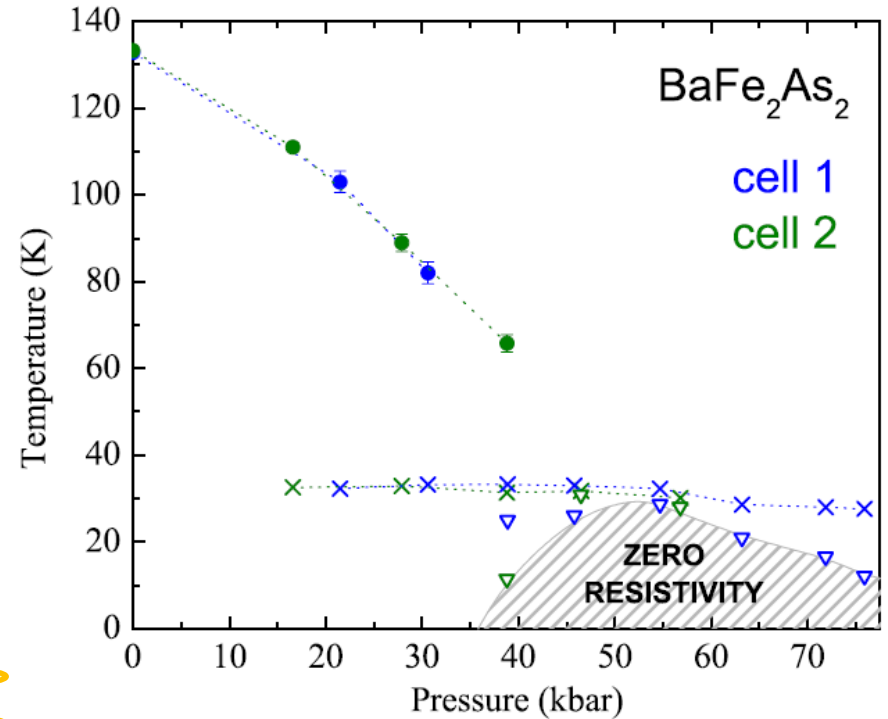
Einflußfaktoren auf Supraleitung

Chemische Dotierung im BaFe_2As_2



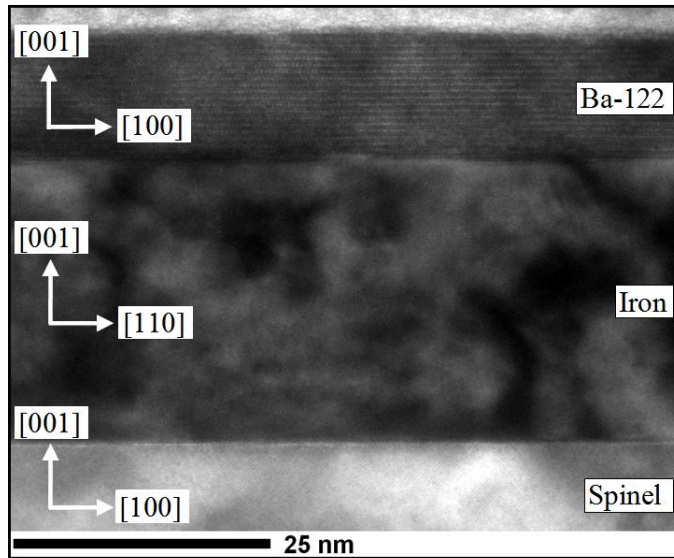
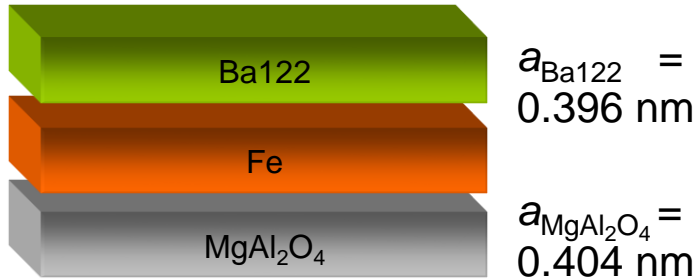
H. Aoki et al., *Physics World* (2015)

Äußerer Druck



E. Colombier et al., *Phys. Rev. B* 79 (2009) 224518

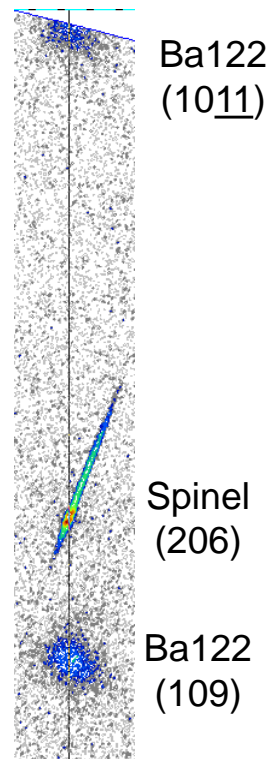
Verspannungsinduzierte Supraleitung in BaFe_2As_2



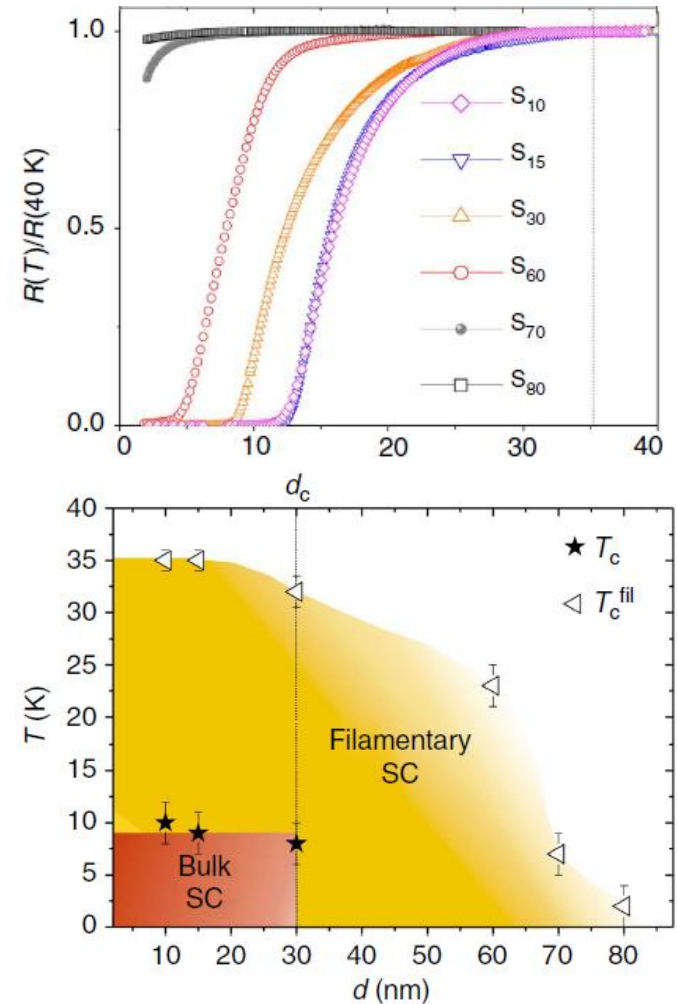
TEM: no defects

Reciprocal Space Map

$d_{\text{Ba122}} = 10 \text{ nm}$



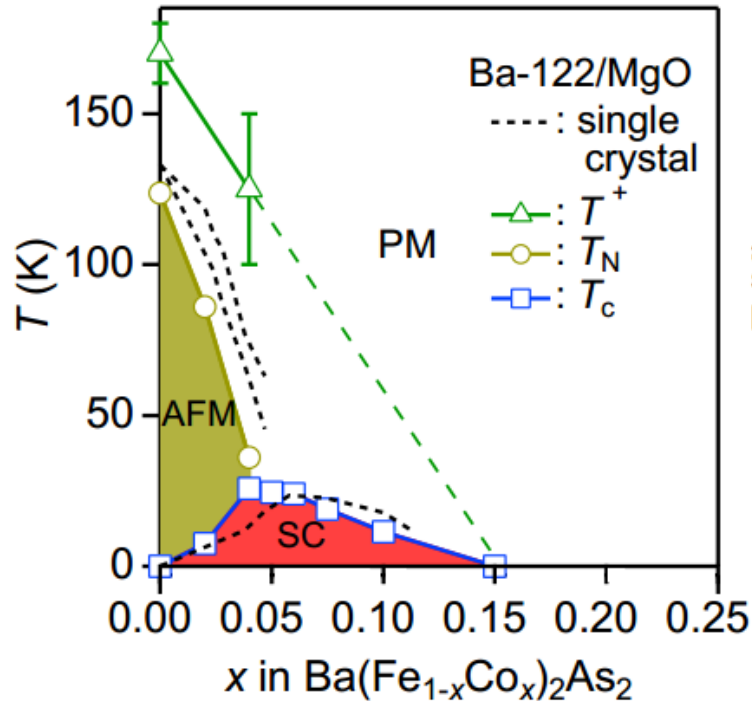
Resistive measurements



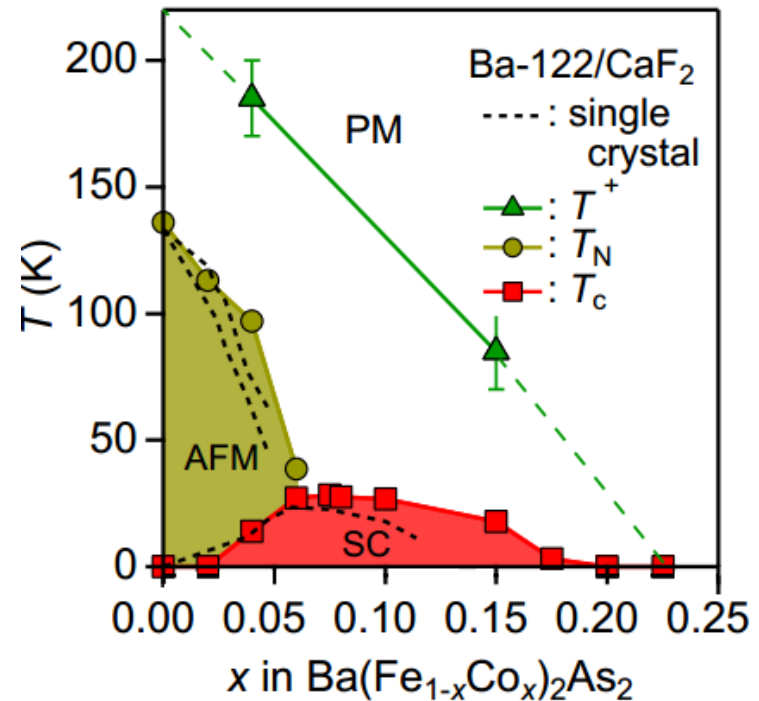
J. Engelmann et al., Nature Comm. 4 (2013) 2877

Einfluß der Verspannung auf $\text{Ba}(\text{Fe}_{1-x}\text{Co}_x)_2\text{As}_2$

Schichten auf MgO:
biaxiale Zugspannung



Schichten auf CaF_2 :
biaxiale Druckspannung

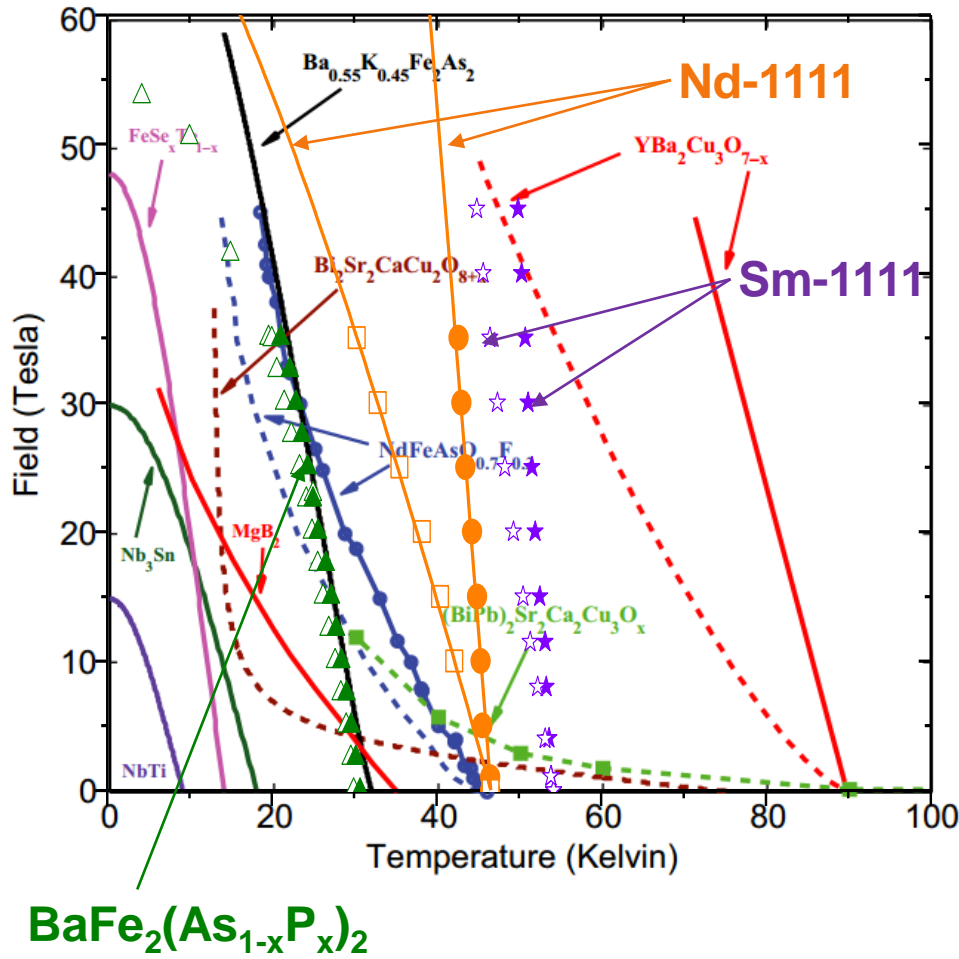


→ Optimale Dotierung ist vom Spannungszustand abhängig!

K. Iida et. al., Sci. Reports (2016) submitted

Eigenschaften in hohen Magnetfeldern

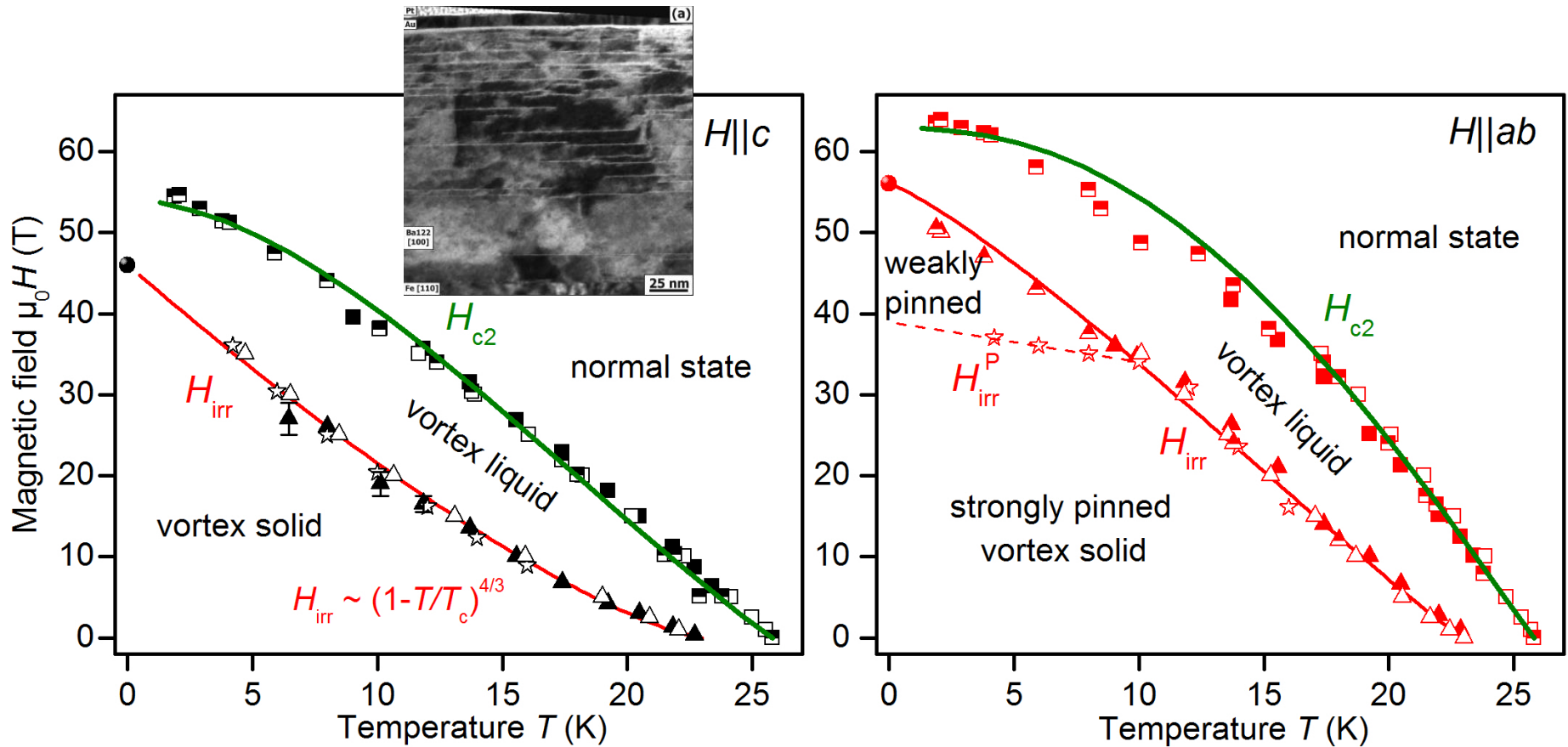
Temperaturabhängigkeit des oberen kritischen Feldes H_{c2}



- Sehr hohe obere kritische Felder
- Geringere Anisotropie im Vergleich zu Kupraten
- Epitaktische MBE-Schichten
- Anstieg für $H_{c2}(T)$ für „1111“ ist unter den höchsten für supraleitende Materialien
- Anisotropie des oberen kritischen Feldes klein für „122“ Verbindungen

A. Gurevich, *Rep. Prog. Phys.* **74**, 124501 (2011)
 K. Iida et al, *Sci Rep*, 3:2139 (2013)
 F. Kurth et al., *Appl. Phys. Lett.* (2015)

Hochfeldmessungen an $\text{Ba}(\text{Fe}_{0.92}\text{Co}_{0.08})_2\text{As}_2$

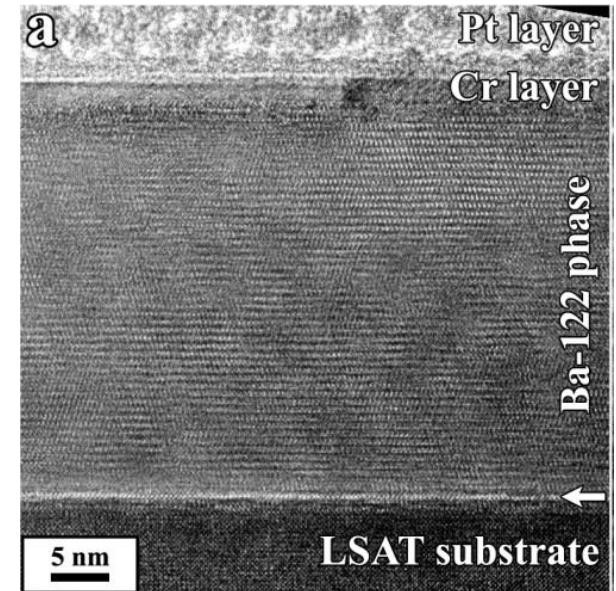
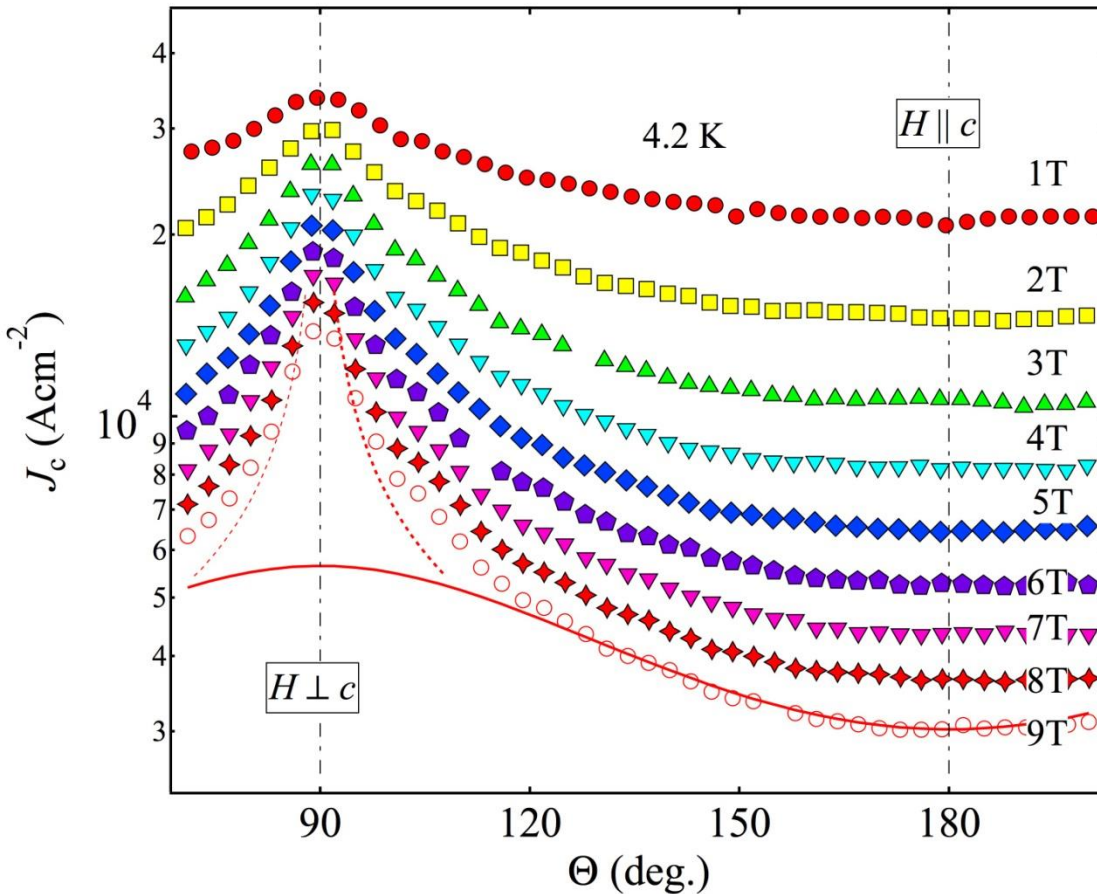


- Temperatur- und Winkelabhängigkeit des oberen kritischen Feldes mit Zweibandmodell erklärbar
- J_c Anisotropie bestimmt von H_{c2} Anisotropie und vorhandenen Defekten

J. Hänisch et al. Sci. Reports 5 (2015) 17363

J_c Anisotropie sauberer Ba122-Schichten

Beispiel $\text{Ba}(\text{Fe}_{0.9}\text{Co}_{0.1})_2\text{As}_2$

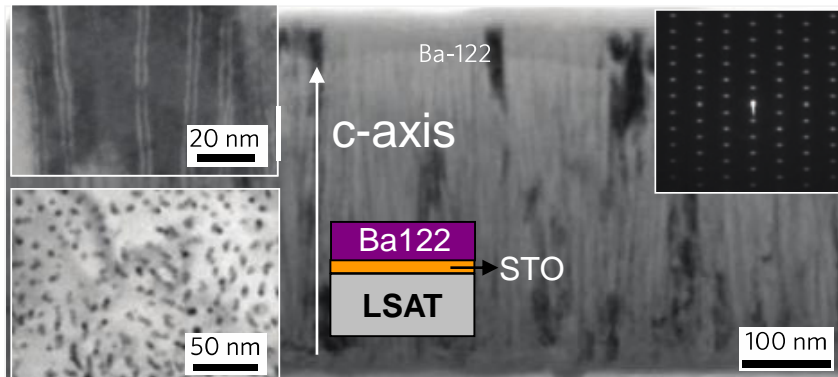


- Relativ geringe absolute J_c Werte
- Maximum bei $B \parallel ab$:
 1. Elektronische Anisotropie
 2. Pinning an planaren Defekten und an Oberflächen
- Kein Maximum für $B \parallel c$: keine korrelierten Defekte

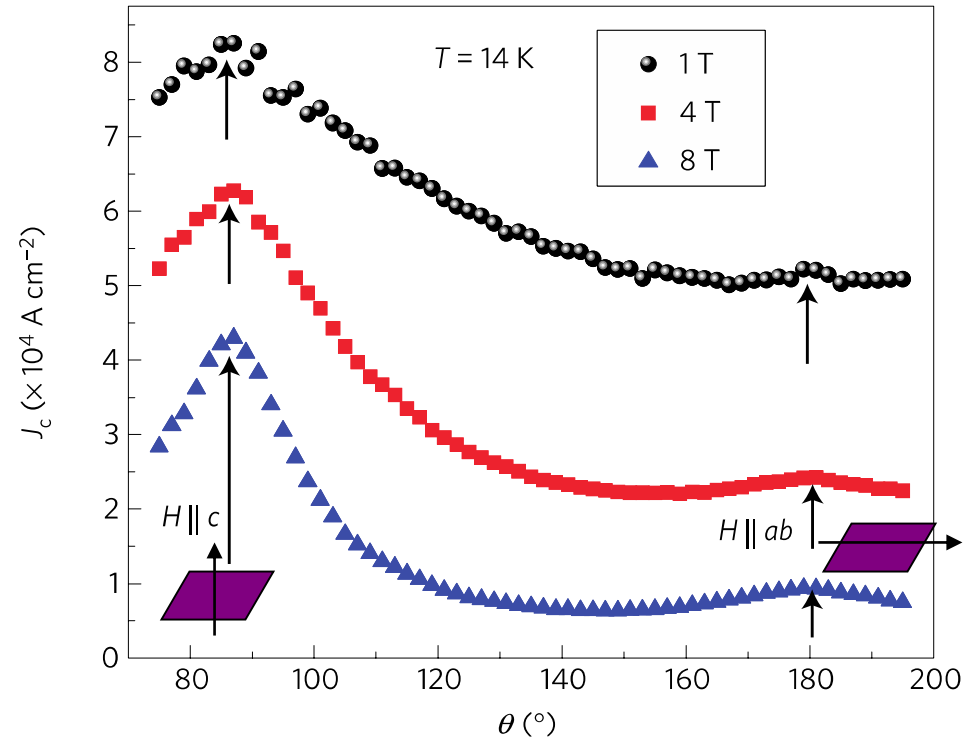
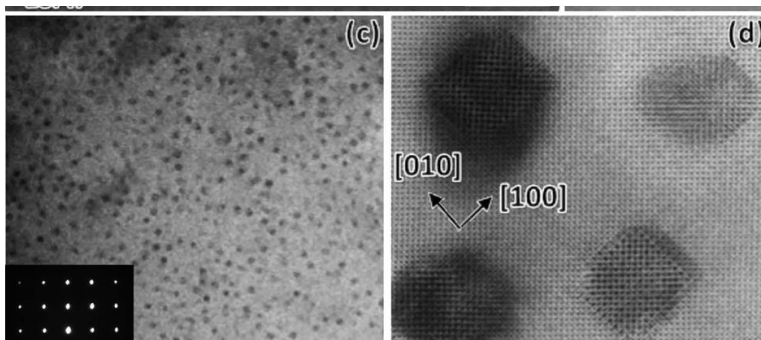
K. Iida et al., PRB 81, 100507(R) (2010)

Pinningzentren in Ba122-Schichten

Pinning an Liniendefekten



Selbstorganisierte BaFeO₂ Nanosäulen



→ Starker c-Achsenpeak

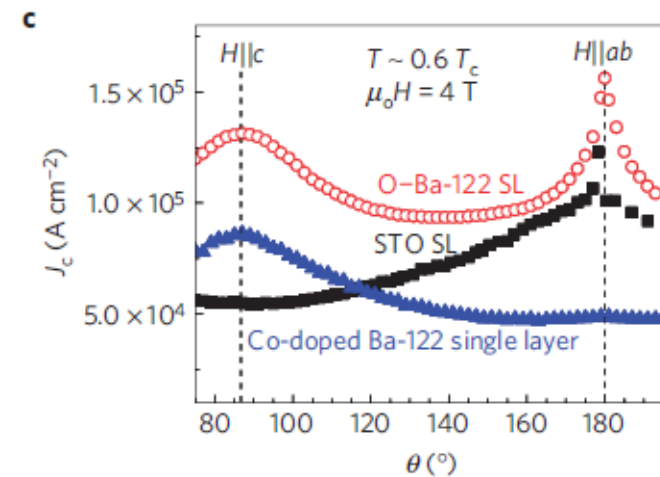
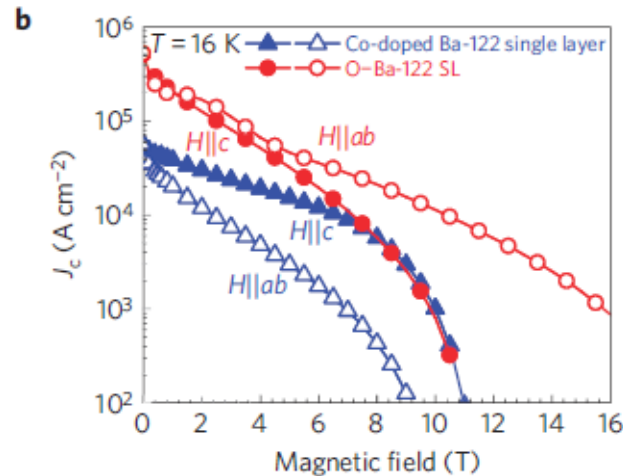
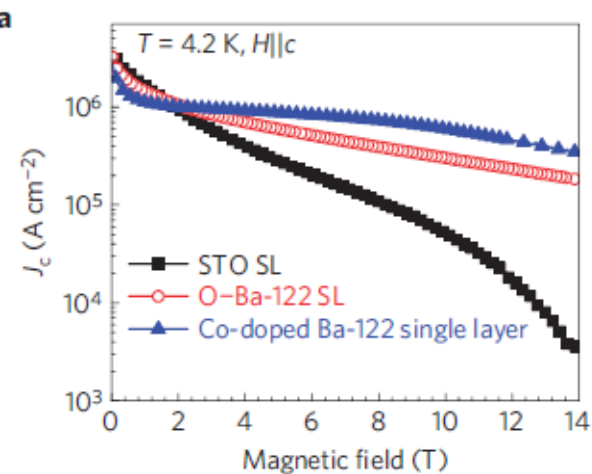
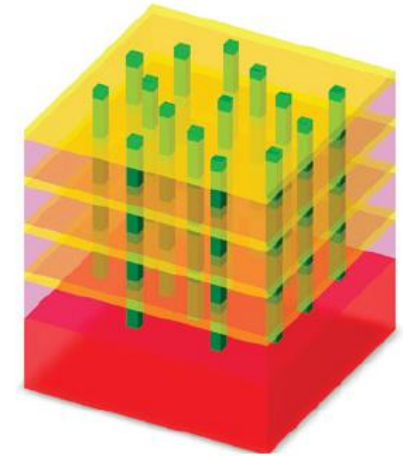
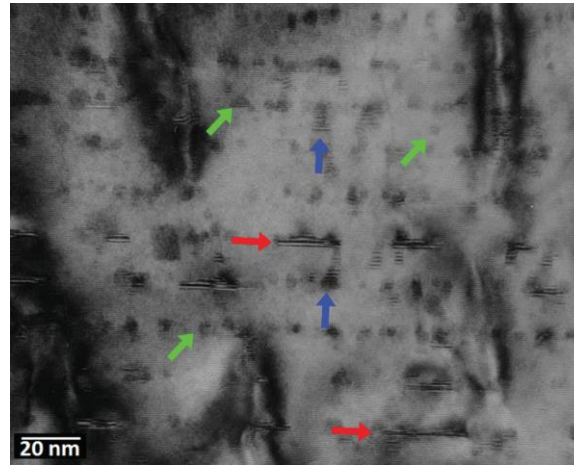
Y. Zhang et al, APL 98, 042509 (2011)

S. Lee et al, Nat. Material 9, 397 (2010)

Pinningzentren in Ba122-Schichten

Quasimultilagen (3D + 1D Defekte)

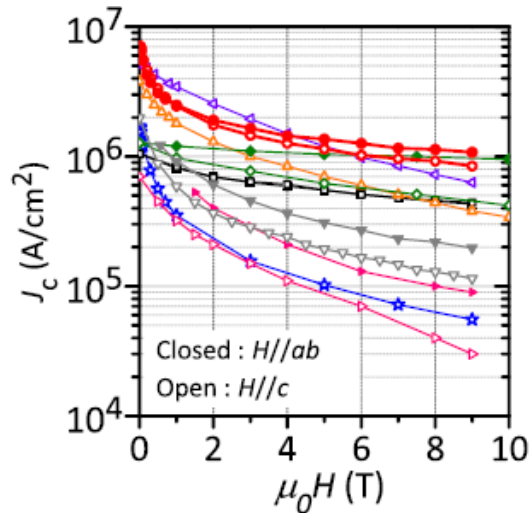
(13.3 nm Co-doped Ba-122
+ 3.3 nm pure Ba-122)x24
Total thickness 400 nm



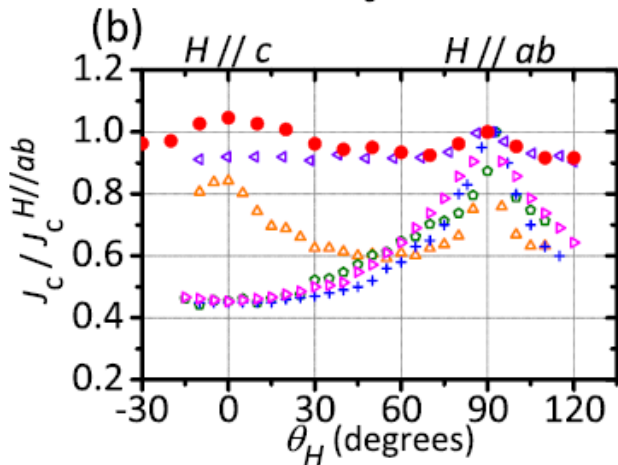
→ Verbesserung von J_c für alle Feldrichtungen

C. Tarantini et al, PRB 86, 214504 (2012)
S. Lee et al., Nat. Mater. 12 (2013) 392

Verbesserung der Pinningeigenschaften



- ○ BaFe₂As₂:P (this work, 4K)
- ◀ BaFe₂As₂:P + BZO (5K, ref.26)
- ◆◇ SmFeAsO_{1-x}F_x (4K, ref.27)
- △ O-rich BaFe₂As₂:Co/BaFe₂As₂:Co SL (4K, ref.28)
- ▶ BaFe₂As₂:Co/Fe buffer (8K, ref.29)
- ▽ BaFe₂As₂:Co/Fe buffer/IBAD-MgO (4K, ref.30)
- □ Fe(Se,Te) (4K, ref.31)
- ★ BaFe₂As₂:Co (4K, ref.32)



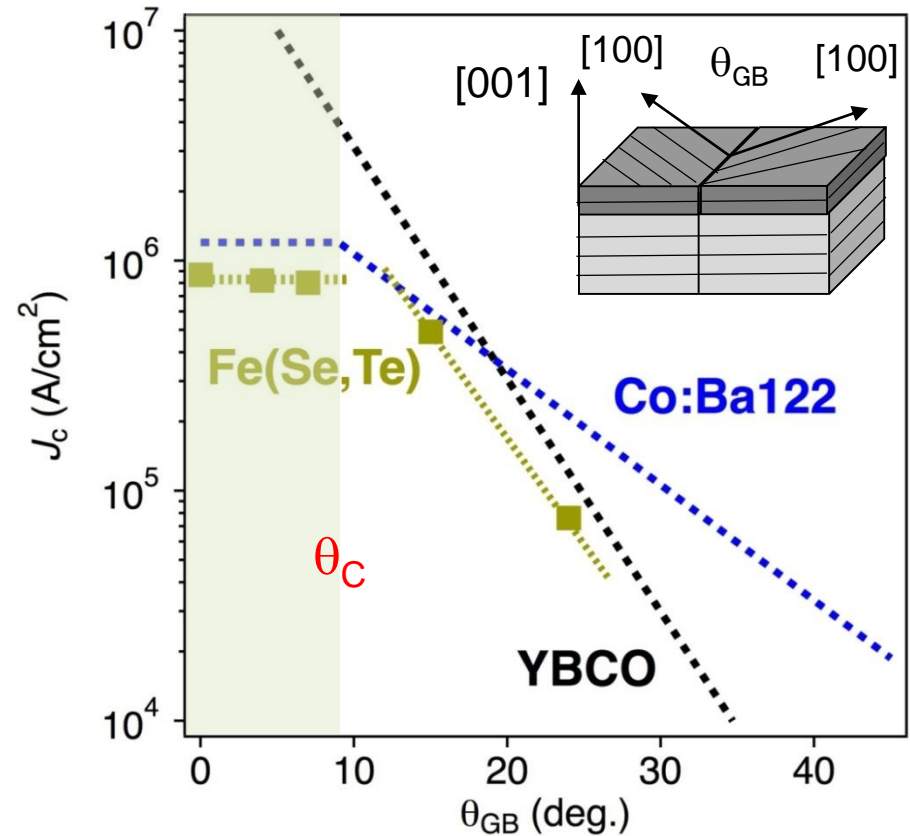
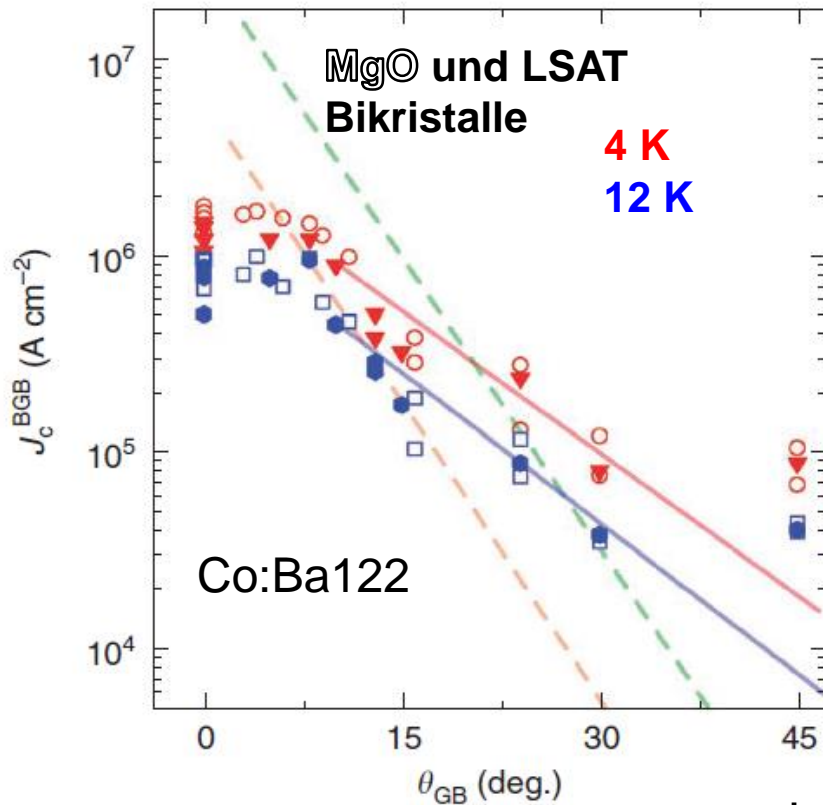
- BaFe₂As₂:P (this work @ 12K, 3T)
- ◀ BaFe₂As₂:P + BZO (15K, 1T, ref.26)
- △ O-rich BaFe₂As₂/BaFe₂As₂:Co SL (14K, 4T, ref.28)
- ◇ STO / BaFe₂As₂:Co SL (11K, 4T, ref.28)
- + BaFe₂As₂:P (10K, 3T, ref.7)
- ▶ BaFe₂As₂:Co/Fe buffer (10K, 3T, ref.29)

H. Sato et al., APL 104 (2014) 182603

→ Vielfältige Variation der Anisotropie möglich wie bei Kupraten

Eigenschaften von Korngrenzen

Epitaktische Schichten auf Bikristallen



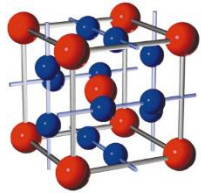
Im Vergleich zu YBCO:

- Größerer Grenzwinkel ($\Theta_c \sim 9^\circ$)
- Schwächerer exponentieller Abfall

T. Katase et al, Nat. Commun. 2 (2011) 409
W. Si et al, Appl. Phys. Lett. 106 (2015) 032602

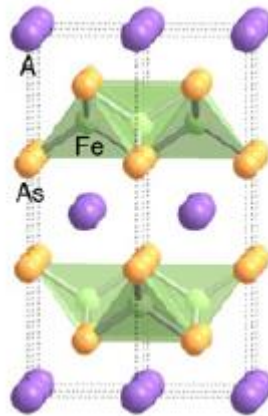
Vergleich zu anderen Supraleitern

Niedrig- T_c SL

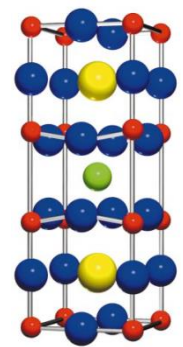


Nb₃Sn

geringe Anisotropie
geringe therm. Fluktuationen
S-Wellen SL
Metallisch



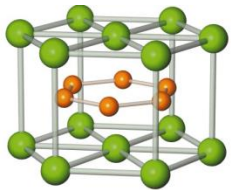
Hoch- T_c SL



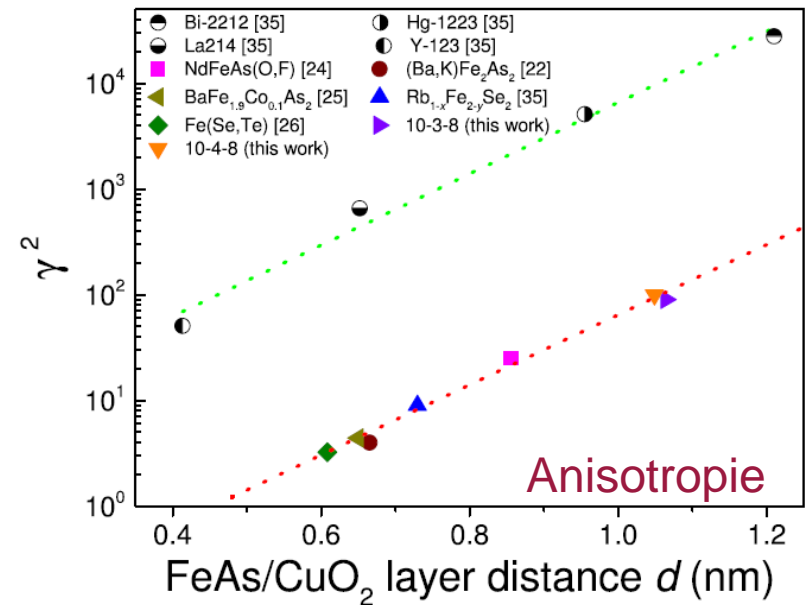
YBa₂Cu₃O₇

Lagenstruktur
Hohes T_c , hohes H_{c2}
Unkonventionelle SL
Starke Korrelationen
Nähe zu mag. Phasen
Korngrenzenproblematik

Multiband-SL (MgB₂)



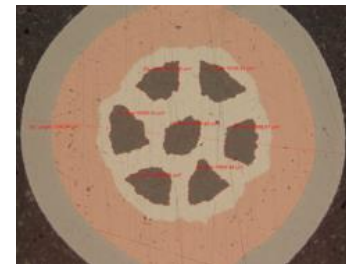
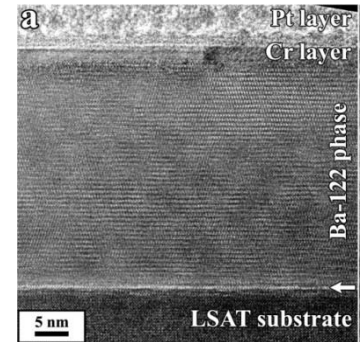
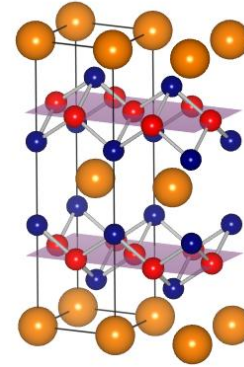
	ξ_{ab} (nm)	λ_{ab} (nm)	T_c (K)	H_{c2} (T)
Nb ₃ Sn	11	200	18	25
YBCO	2.2	120	92	>100
MgB ₂	10	50	37	14
Ba-122	3	200	25	60
Sm-1111	2.5	200	55	> 100
Fe(Se,Te)	1.5	500	16	55



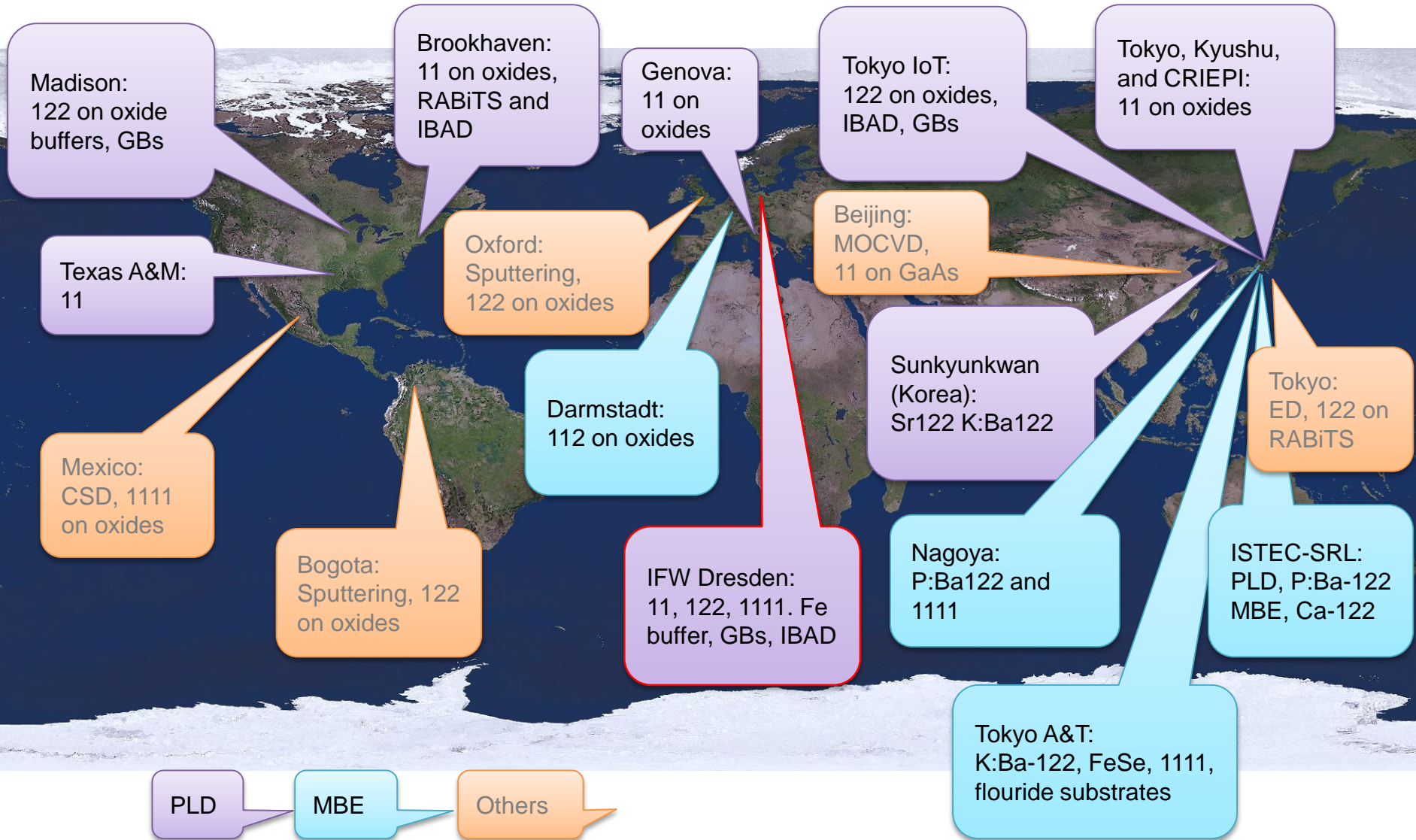
F. Yuan et al., APL 107 (2015) 012602

Inhalt

- Grundlegende Eigenschaften
 - Materialien
 - Phasendiagramm
 - Verhalten im Magnetfeld
 - Stromtragfähigkeit
- Herstellung von Leitermaterialien
 - Dünnschichtherstellung
 - PIT Technologie
- Anwendungsperspektiven

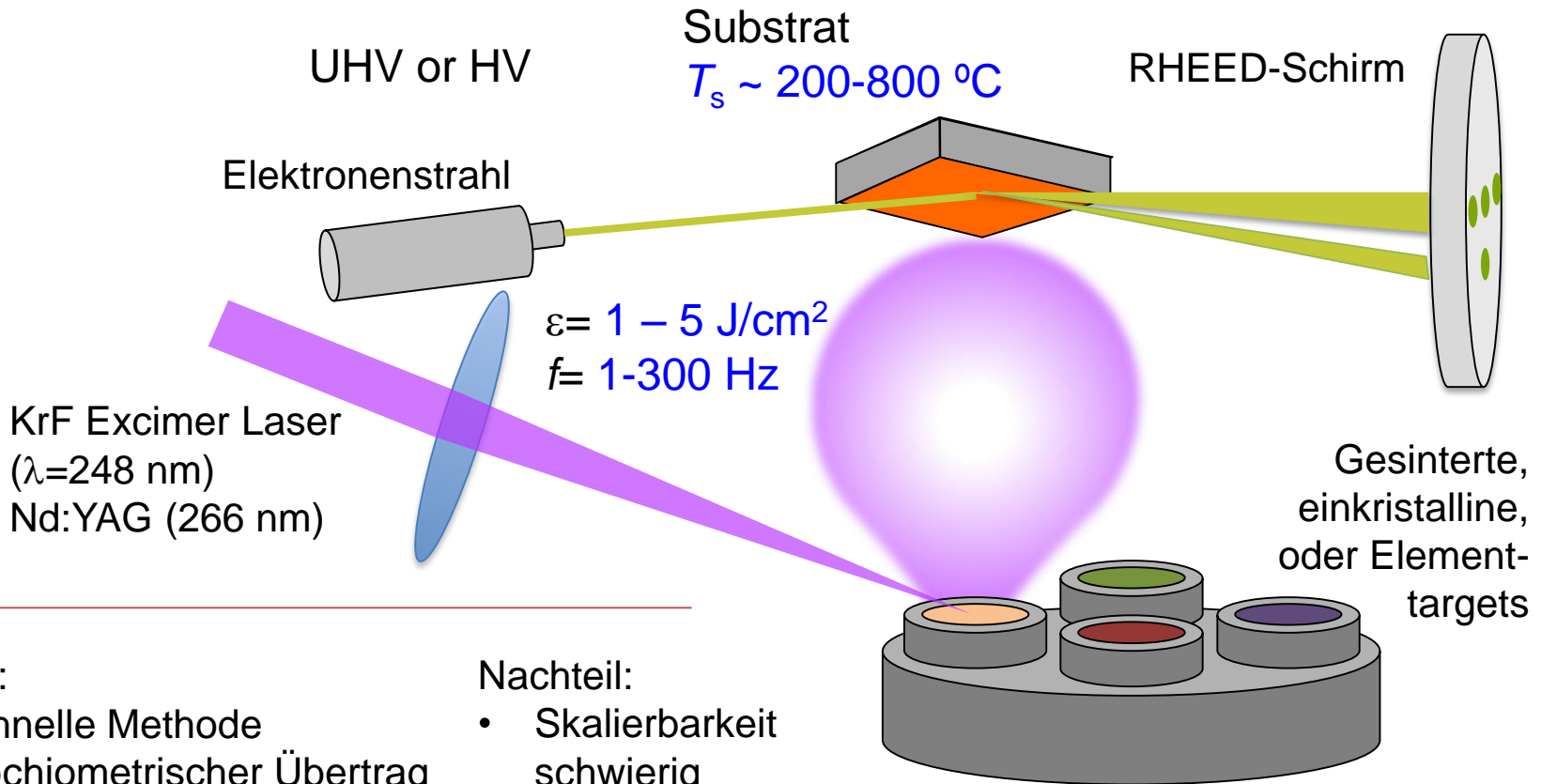


Dünnschichten Fe-basierter Supraleiter



Fe-basierte Dünnschichten mit PLD

Gepulster Laserstrahl auf Target → stöchiometrisches Plasma des Targetmaterials
→ Abscheidung auf Substrate



Vorteil:

- Schnelle Methode
- Stöchiometrischer Übertrag
- Lagenwachstum möglich

Nachteil:

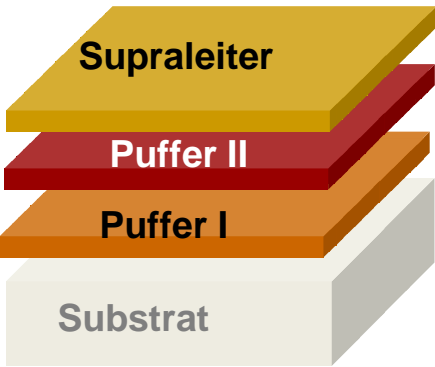
- Skalierbarkeit schwierig
- Manchmal Droplets

Fe-basierte Dünnschichten mit PLD

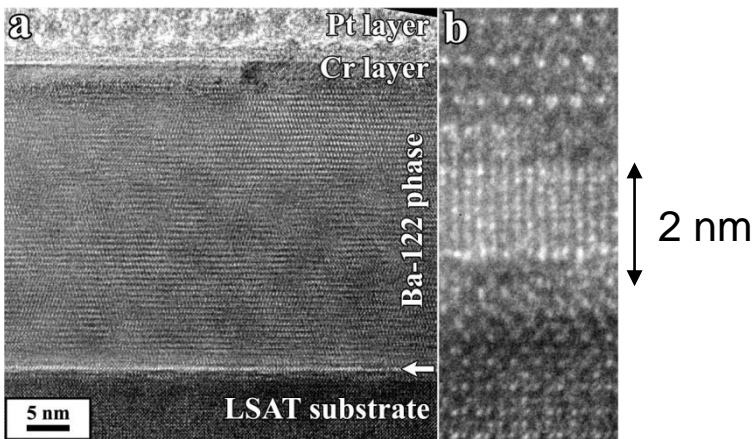
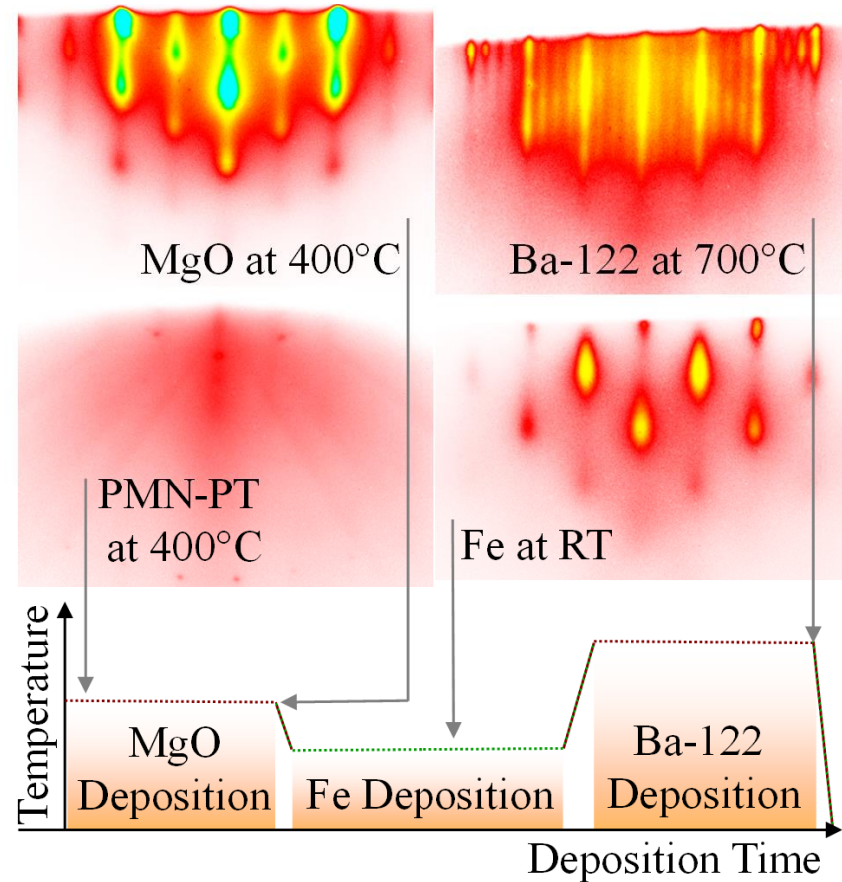
Herstellung in einem UHV setup unter in-situ RHEED Kontrolle

Substrate:

- Oxidische Einkristalle (MgO, LaAlO₃ etc.)
- Fluorit-Einkristalle (CaF₂, BaF₂, SrF₂)
- Piezokristalle (PMN-PT)
- Flexible Metallbänder (Hastelloy/IBAD-MgO)



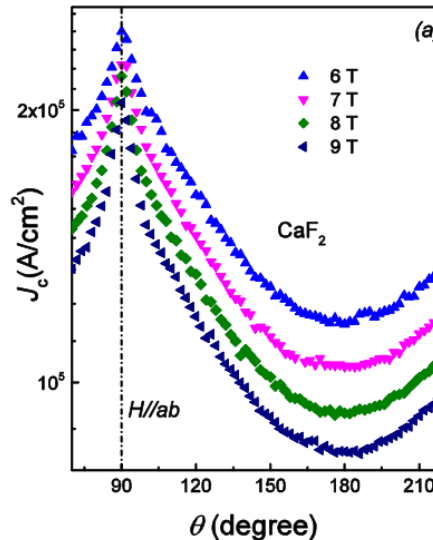
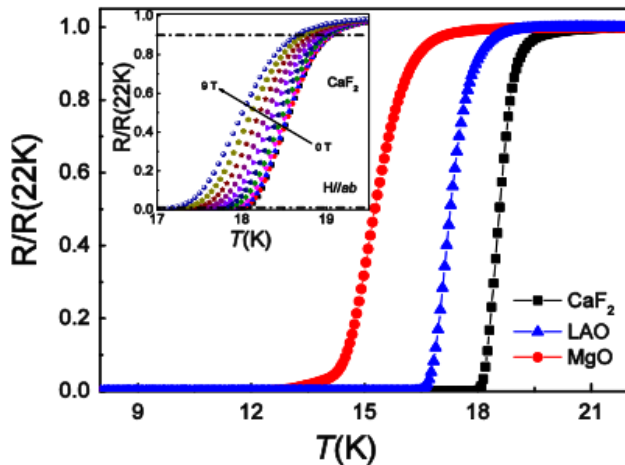
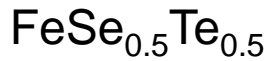
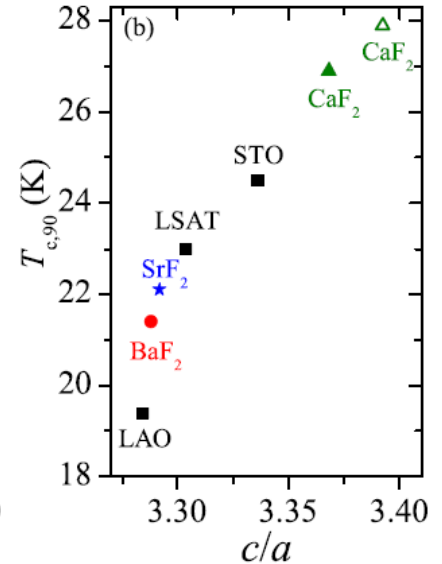
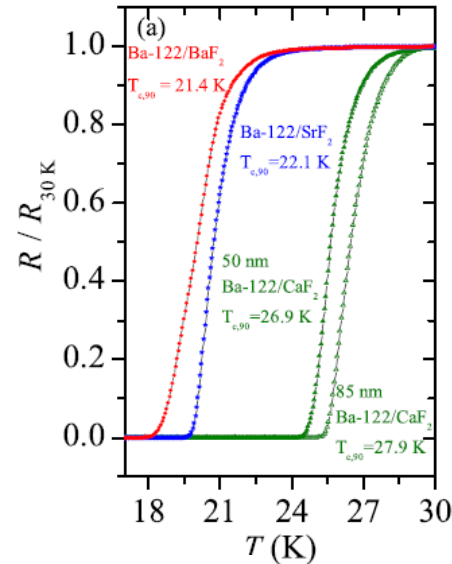
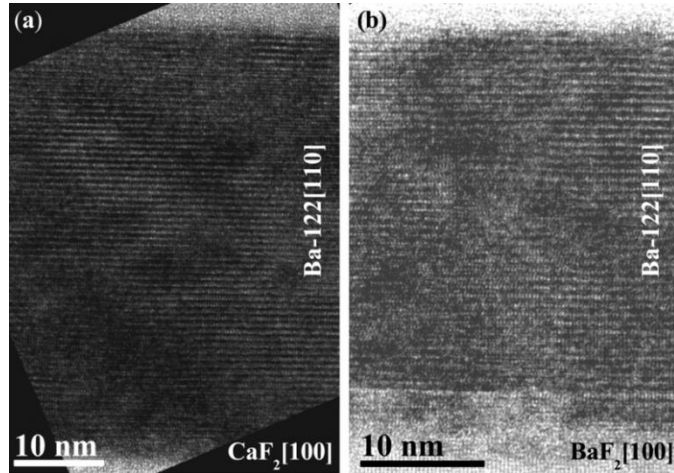
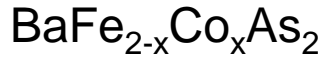
Schichtarchitektur



K. Iida et al, PRB 81, 100507 (2010)

S. Trommler et al., J. Phys.: Conf. Ser. 507 (2014) 012049

Substratabhängigkeit Fe-basierte Dünnschichten



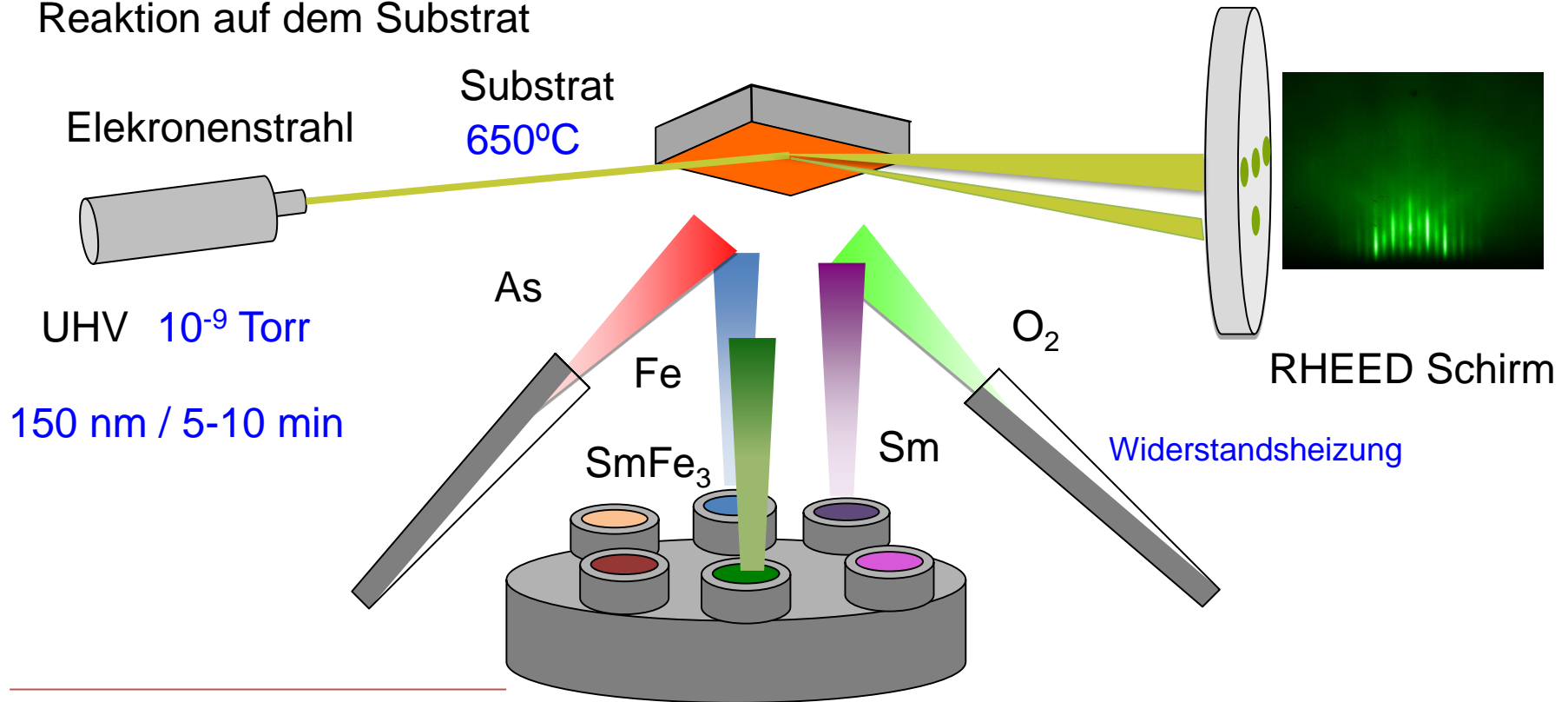
F. Kurth et al., APL 102, 142601 (2013)

➤ Schichten auf CaF_2 haben höchste T_c

F. Yuan et. al., SUST 28 (2015) 065005

Fe-basierte Dünnschichten mit MBE

Einzelne Quellen (e.g. Knudsenzellen) → atomare oder „molekulare“ Ströme → Reaktion auf dem Substrat



Vorteile:

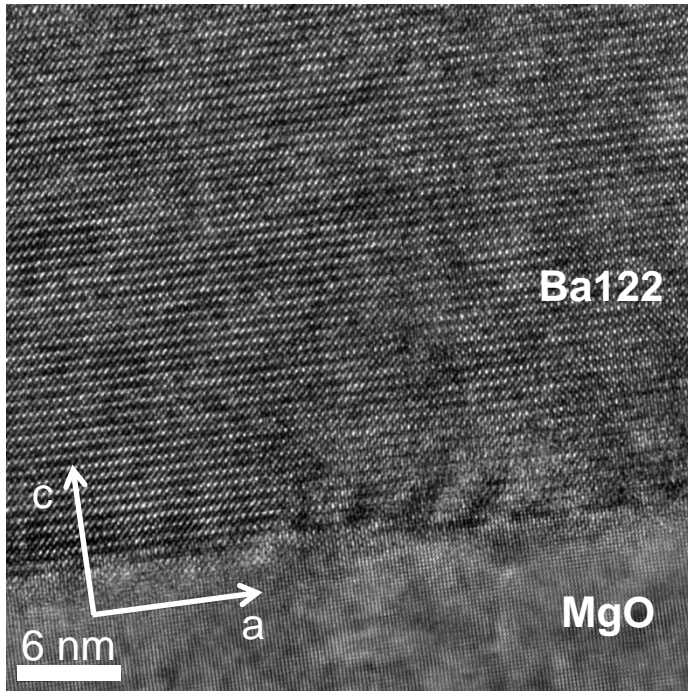
- Langsame Deposition möglich
- Saubere Schichten
- Gute Epitaxy

Nachteile:

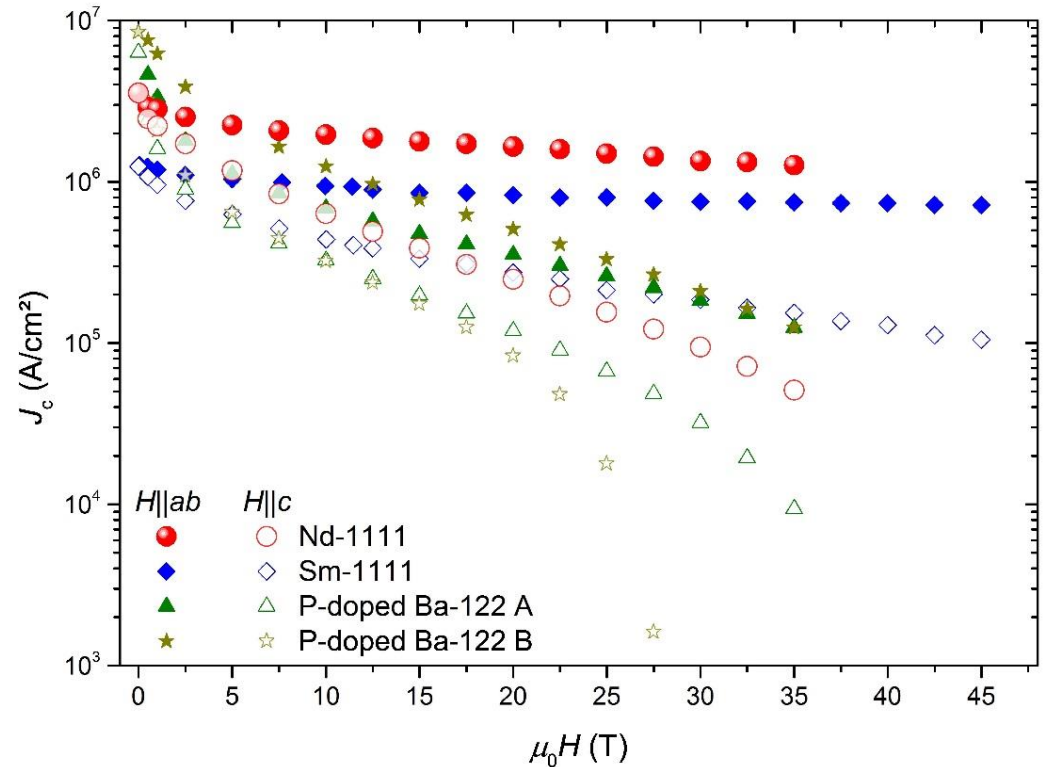
- Relative teuer
- UHV notwendig (geringe Raten!)

Fe-basierte Dünnschichten mit MBE

TEM BaFe₂(As_{1-x}P_x)₂



Kritische Stromdichte J_c



→ Hohe Strukturqualität

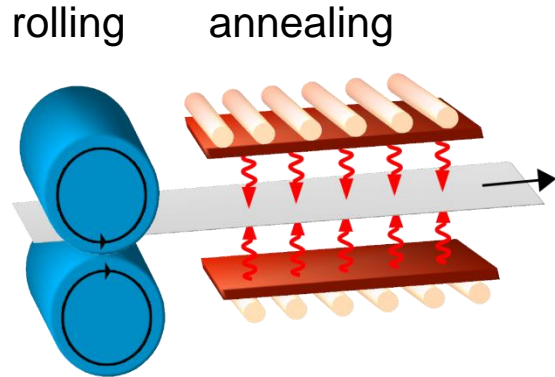
→ Sehr hohe J_c (B) Werte mit geringer Magnetfeldabhängigkeit

K. Iida et al, Sci. Rep, 3:2139 (2013)

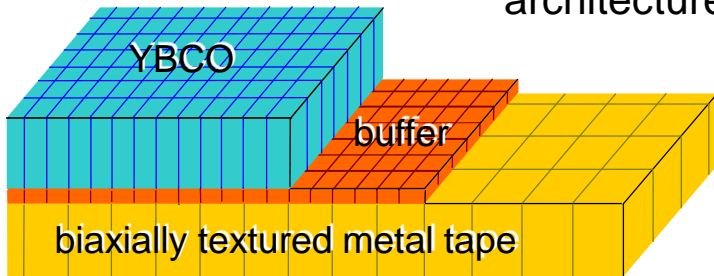
F. Kurth et al., APL 106 (2015) 072602

Hochtexturierte flexible Template

Rolling Assisted Biaxially Textured Substrates (RABITS)

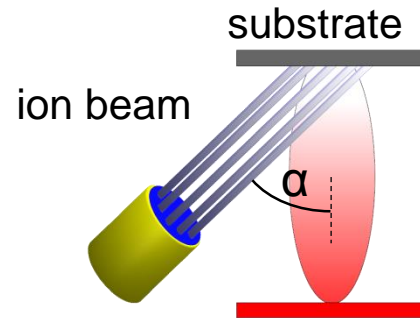


epitaxial deposition of buffer architecture



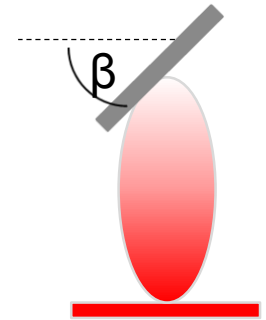
→ Biaxial texturiertes Substrat

Ion Beam Assisted Deposition (IBAD)

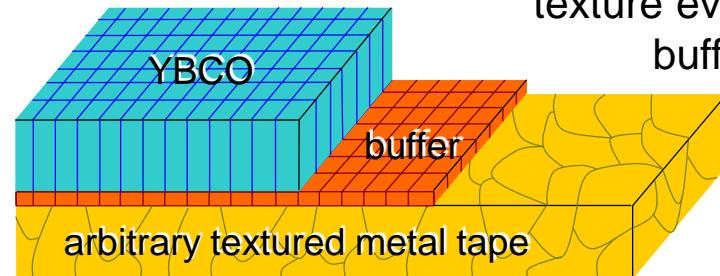


PLD,
e-beam,
sputtering

Inclined Substrate Deposition (ISD)



texture evolves in
buffer layer



→ Biaxial texturierte Pufferschicht

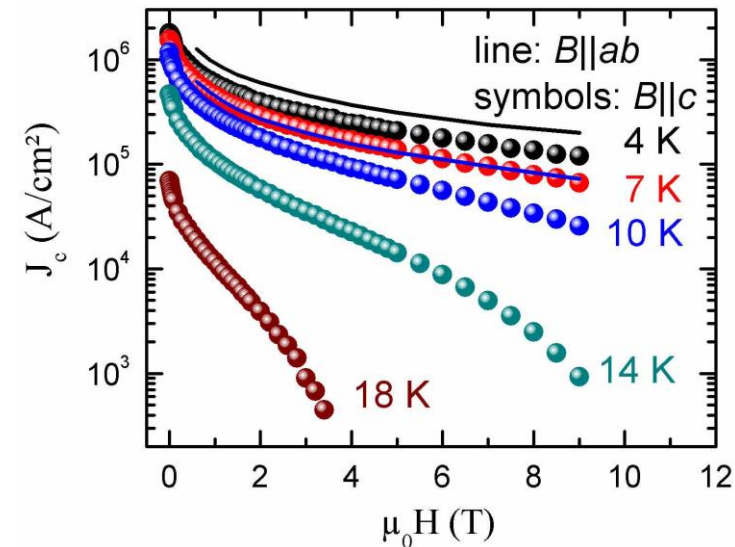
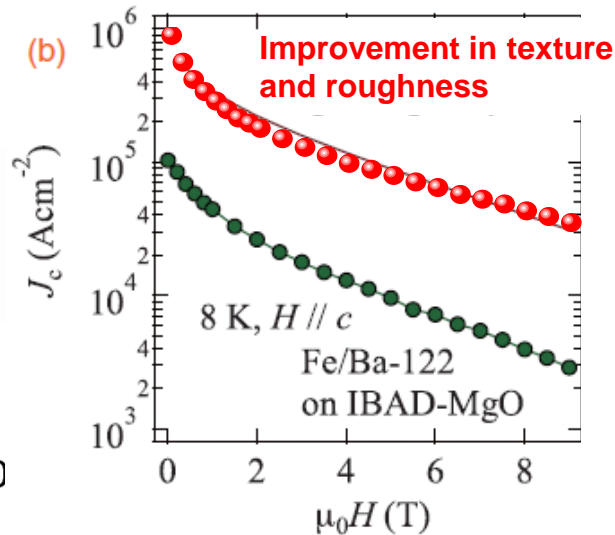
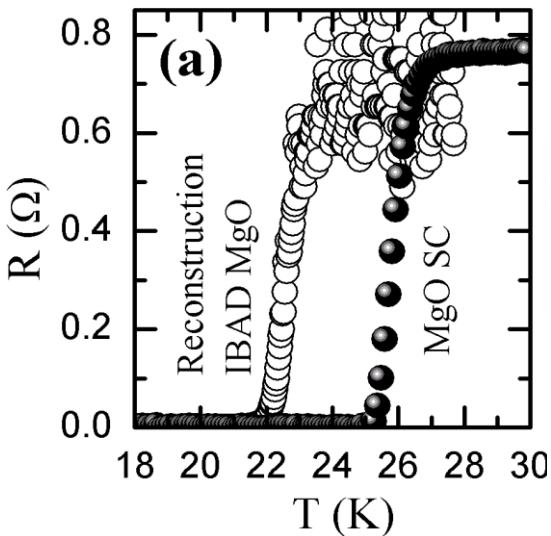
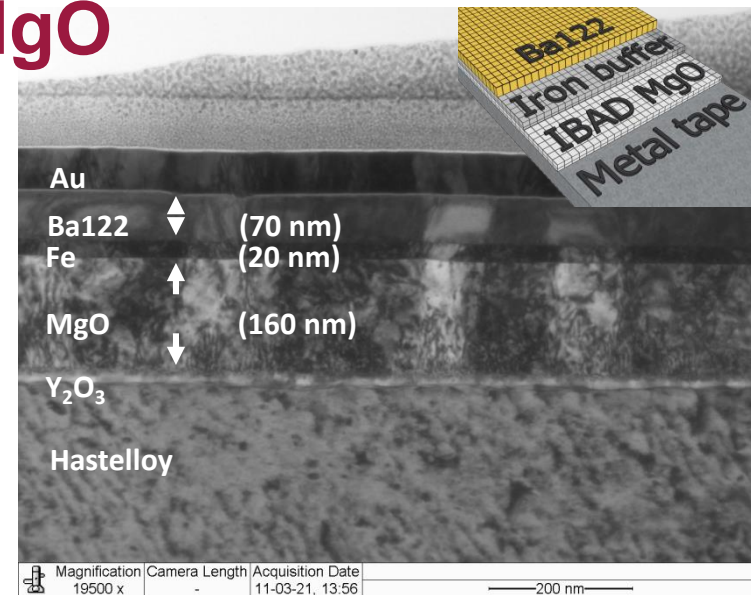
Eignung auch für Fe-basierte Supraleiter

Co dotiertes Ba122 auf IBAD-MgO

- Ba-122 Schichten erfolgreich abgeschieden
- In-plane FWHM für Ba-122 bis zu 1.7°
- Supraleitende Eigenschaften vergleichbar zu Schichten auf MgO Einkristallen

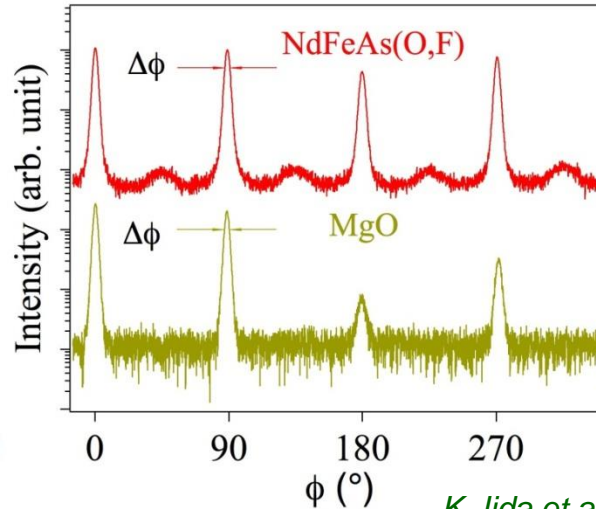
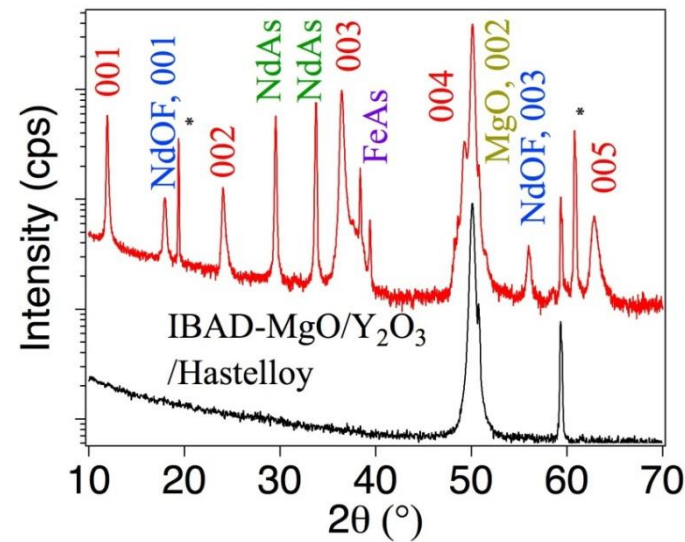
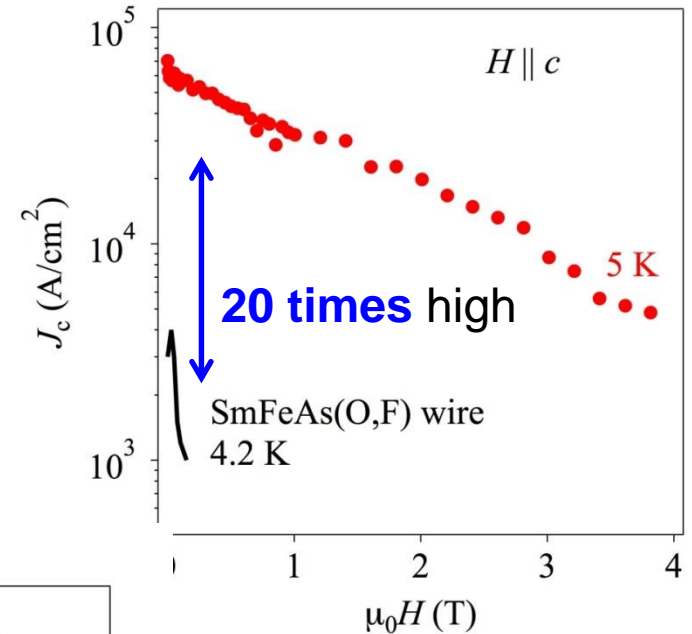
K. Iida et al. APEX 4 (2010) 013103

S. Trommler et al. SUST 25 (2012) 084019



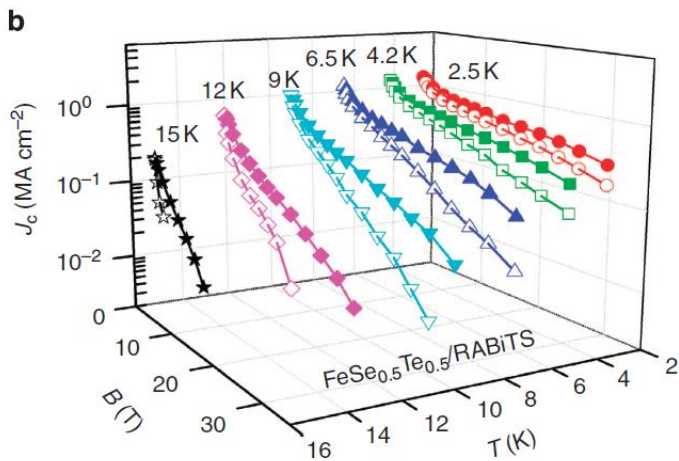
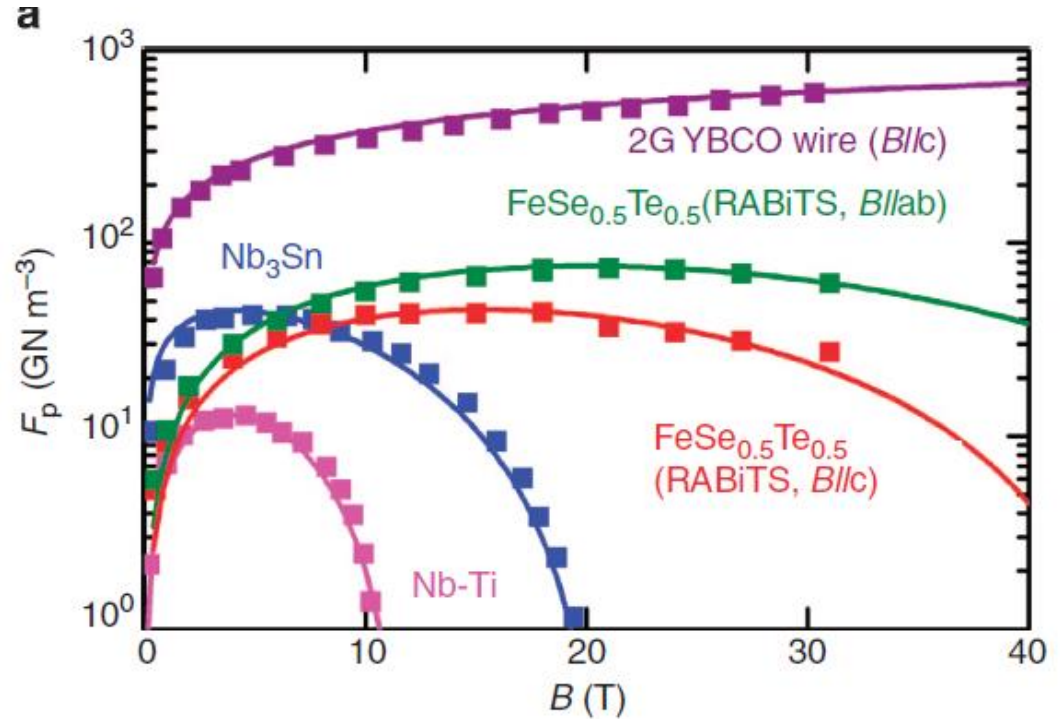
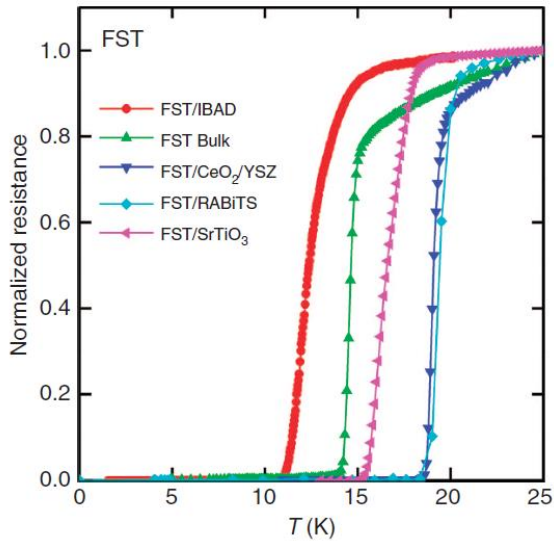
Nd-1111 auf IBAD-MgO mit MBE

- ✓ Epitaktisches Wachstum möglich, aber Fremdphasen vorhanden
- ✓ Kleiner Anteil 45° rotierter Körner



K. Iida et al. Appl. Phys. Lett. 105, 172602 (2014)
M. Fujioka et al. Appl. Phys. Express 4, 063102 (2011)

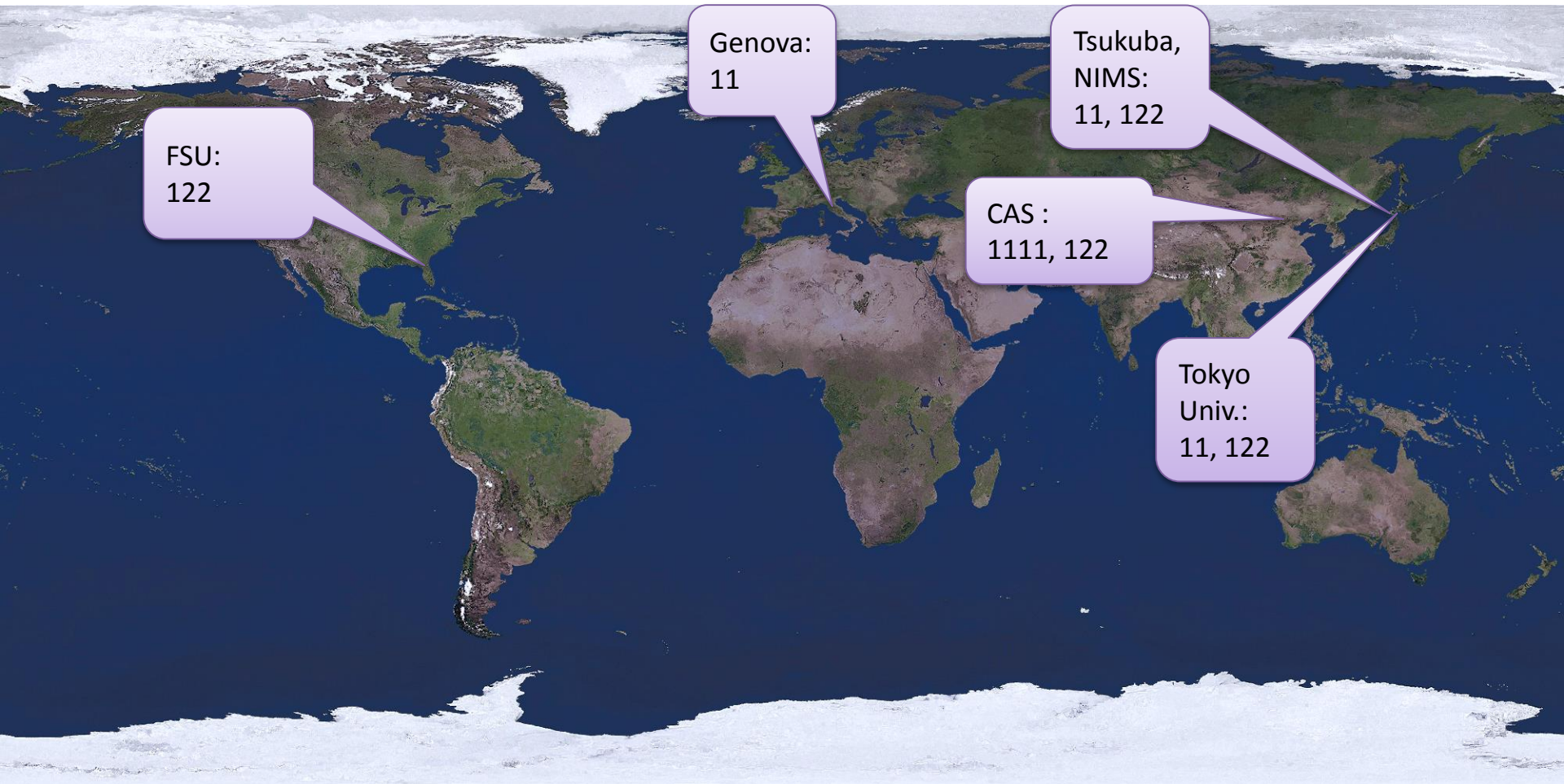
FeSe_{0.5}Te_{0.5} auf RABiTS mit PLD



→ Epitaktisches Wachstum möglich
 → Hohe Stromtragfähigkeit bei 4.2 K

W. Si et al., Nat. Comm. 4, 1347 (2013)

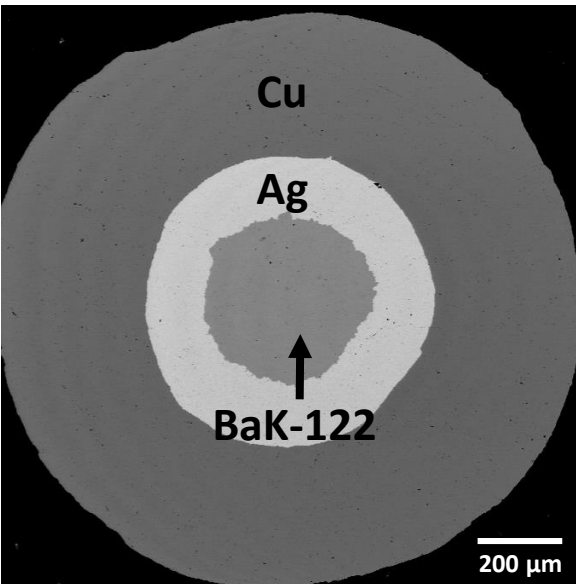
Powder in tube (PIT) Leiterentwicklung



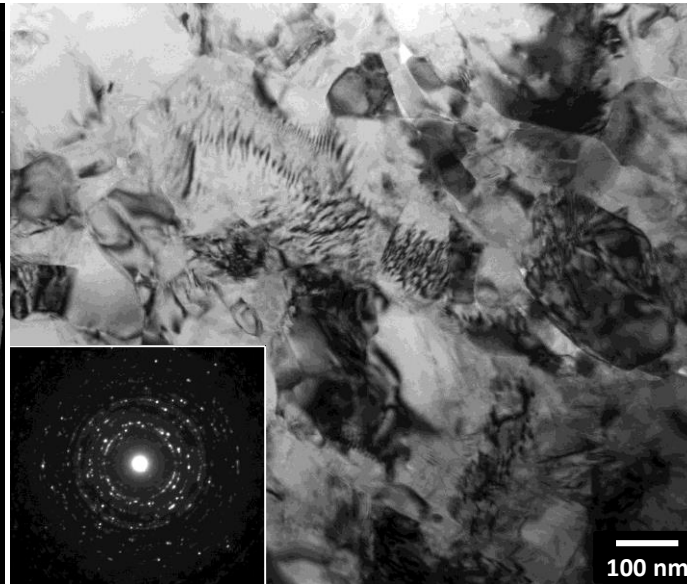
PIT

Powder in tube (PIT) Leiter

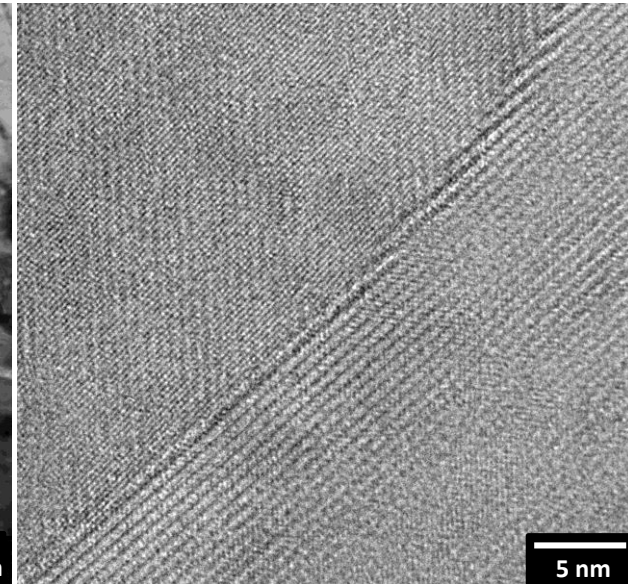
Mechanisch legierter $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$ Leiter
(NHMFL Tallahassee)



SEM Querschnitt



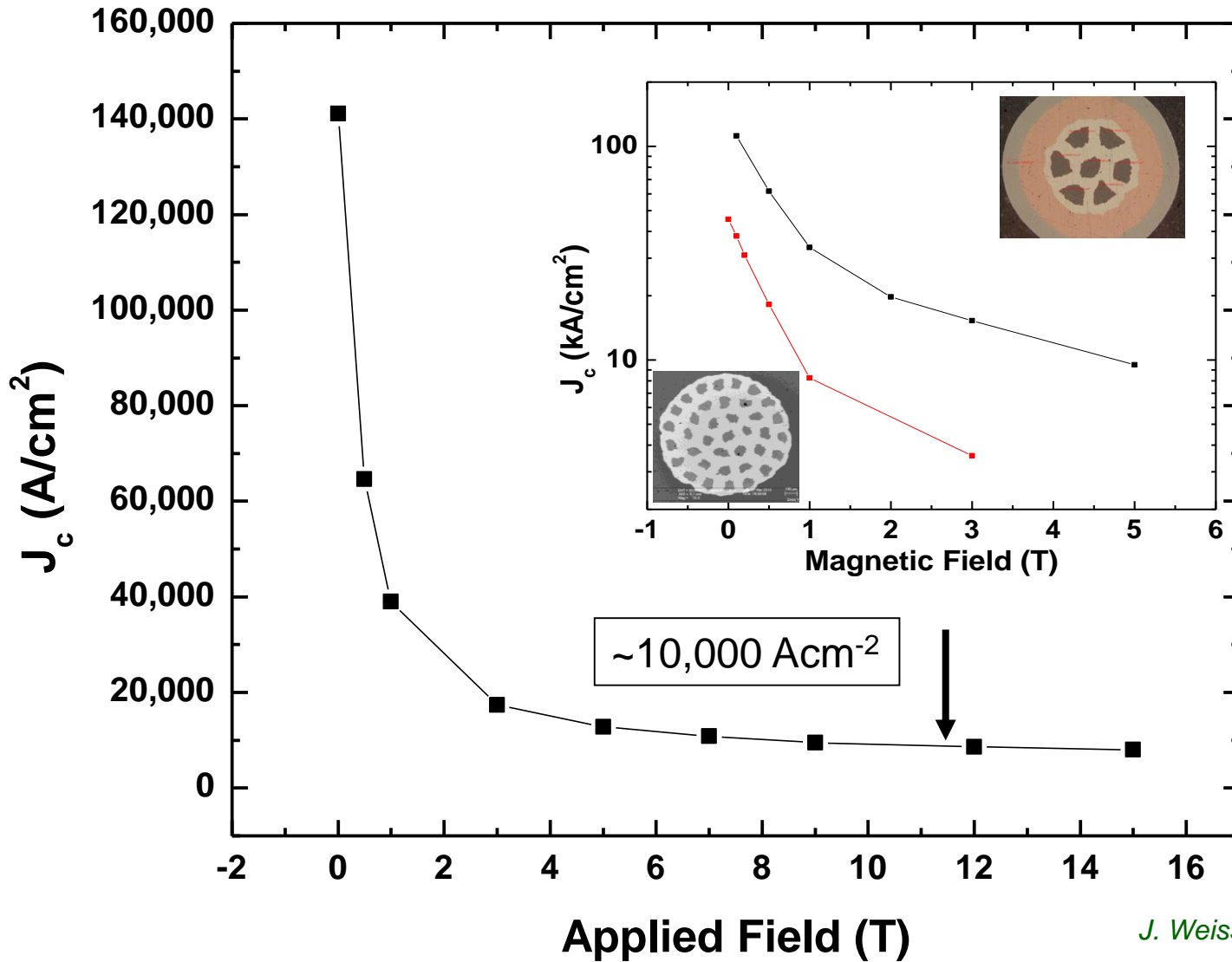
TEM Aufnahme des feinkörnigen
Gefüges



HRTEM Aufnahme einer
 $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$ Korngrenze

J. Weiss et al., Nat. Mater. 11 (2012) 682

Powder in tube (PIT) Leiter

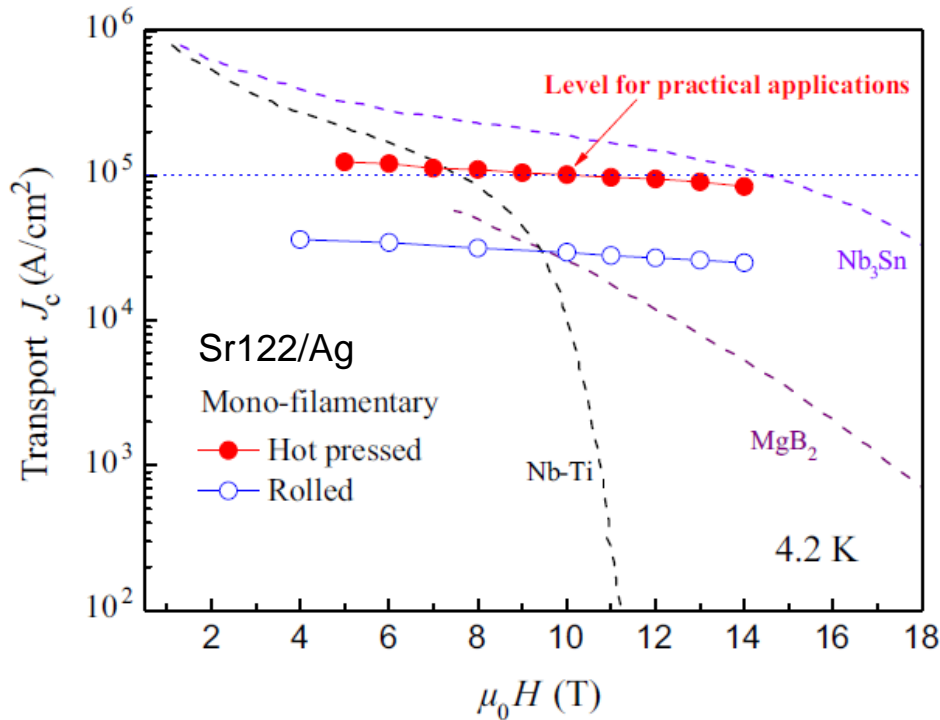


Transport J_c ist viel größer als erwartet!

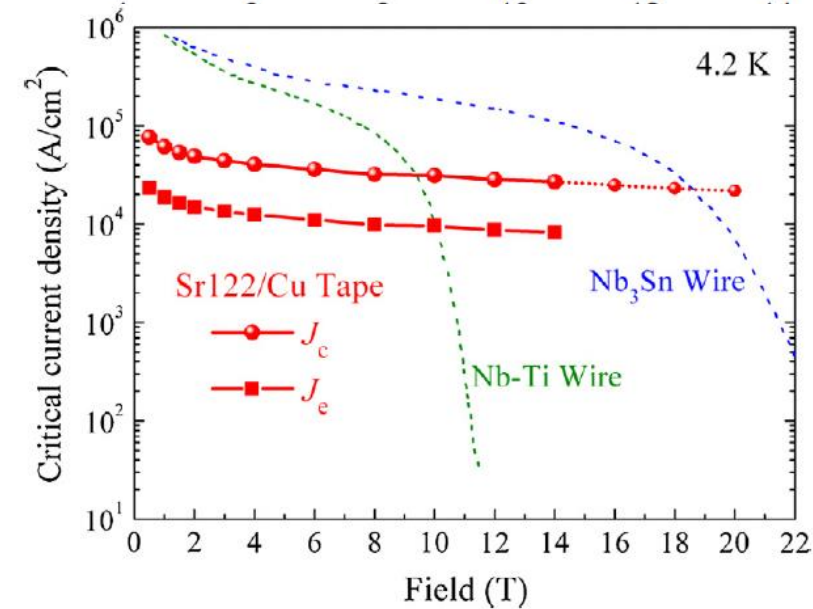
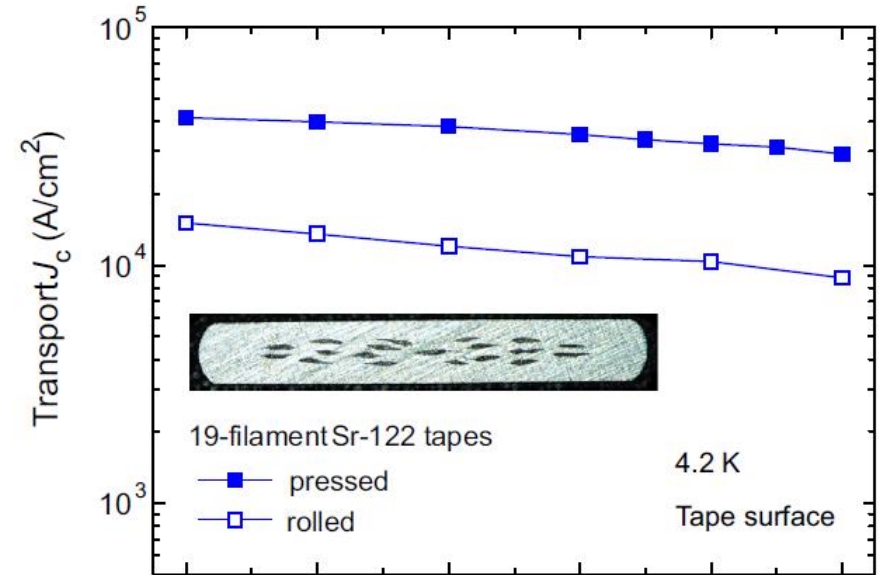
J. Weiss et al., Nat. Mater. 11 (2012) 682

PIT Leiter

Ex-situ $\text{Sr}_{0.6}\text{K}_{0.4}\text{Ba}_2\text{As}_2$ -Leiter (CAS Peking)

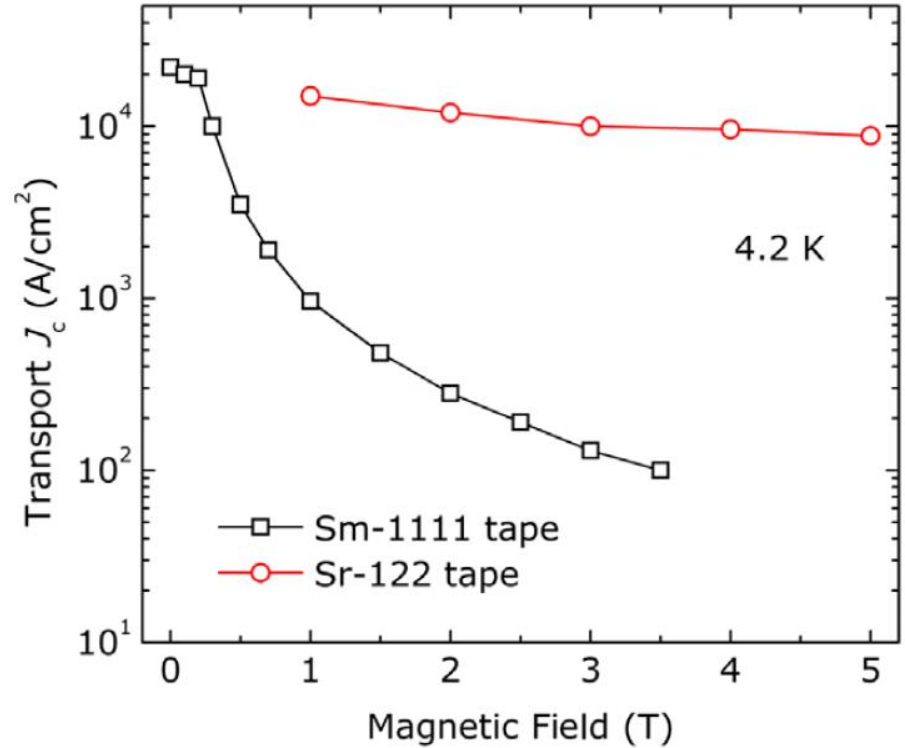
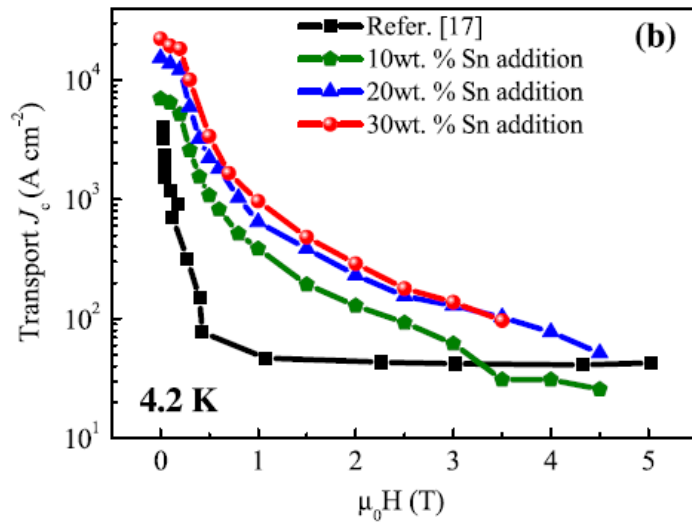
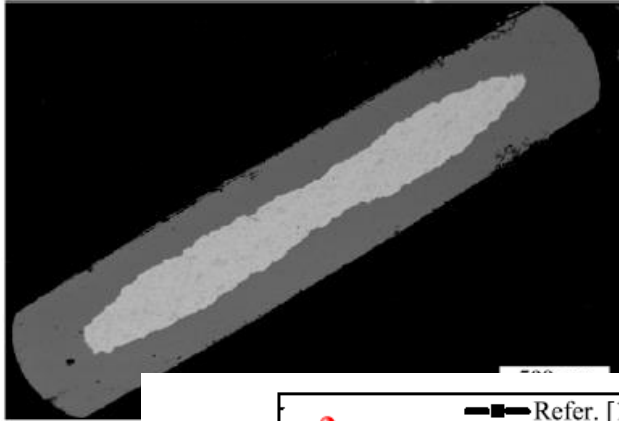


Y. Ma, *Physica C* 516 (2015) 17



PIT Leiter

Ex-situ Sn:SmFeAsO_{1-x}F_x Leiter (CAS Peking)

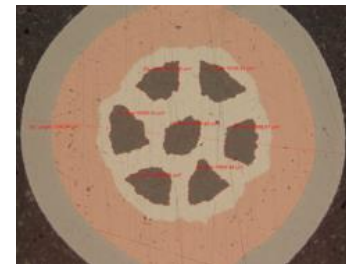
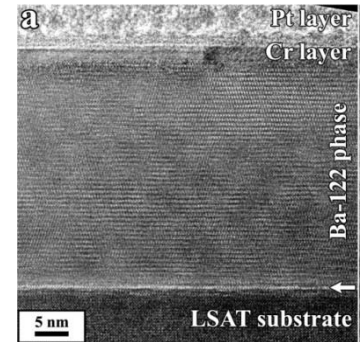
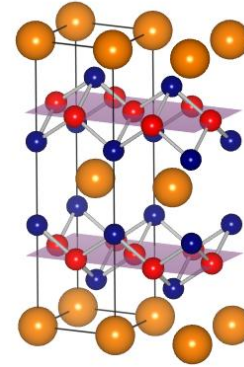


C. Wang et al., SUST 26 (2013) 075017

C. Yao et al., SUST 27 (2014) 044019

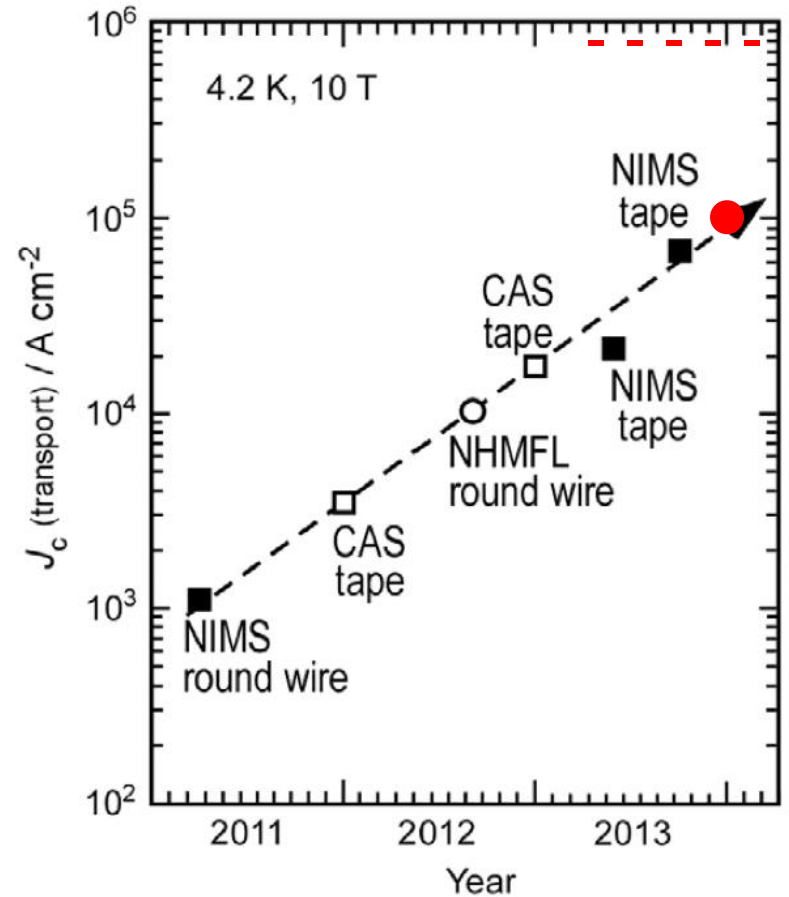
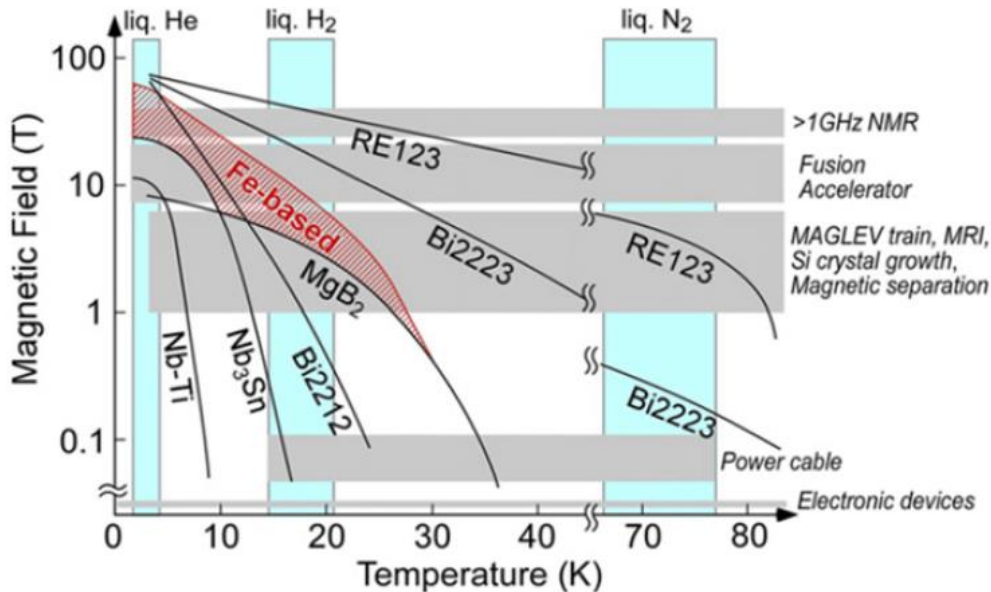
Inhalt

- Grundlegende Eigenschaften
 - Materialien
 - Phasendiagramm
 - Verhalten im Magnetfeld
 - Stromtragfähigkeit
- Herstellung von Leitermaterialien
 - Dünnschichtherstellung
 - PIT Technologie
- Anwendungsperspektiven



Anwendungsperspektiven

- Derzeit begrenztes Anwendungsgebiet
- Technologie für runde Drähte entwickelt sich schnell!
- Zusätzliche Anwendungen für SQUIDS und Strahlungsdetektoren



- Improved CAS tape
- Current Ba122 film limit

J. Shimoyama, *Supercond. Sci. Technol.* **27** (2014) 044002

Danksagung

- IFW: V. Grinenko, F. Kurth, J. Engelmann, S. Richter, F. Yuan, S. Trommler, E. Reich, T. Thersleff, M. Kidszun, S. Molatta, S. Haindl, M. Schulze, S. Aswartham, S. Wurmehl, B. Büchner, L. Schultz
- University Nagoya: K. Iida, H. Ikuta + group
- KIT: B. Holzapfel, J. Hänisch, M. Langer
- TU Dresden: P. Chekhonin, A. Pukenas, W. Skrotzki
- NHMFL Tallahassee: C. Tarantini, J. Jaroszynski
- SPIN Genova: M. Putti, C. Ferdeghini + group
- many more...



Exploring the potential
of Iron-based Superconductors

Danke für Ihre Aufmerksamkeit!