Growth pressure effects and physical properties of high T_c iron-based superconductors

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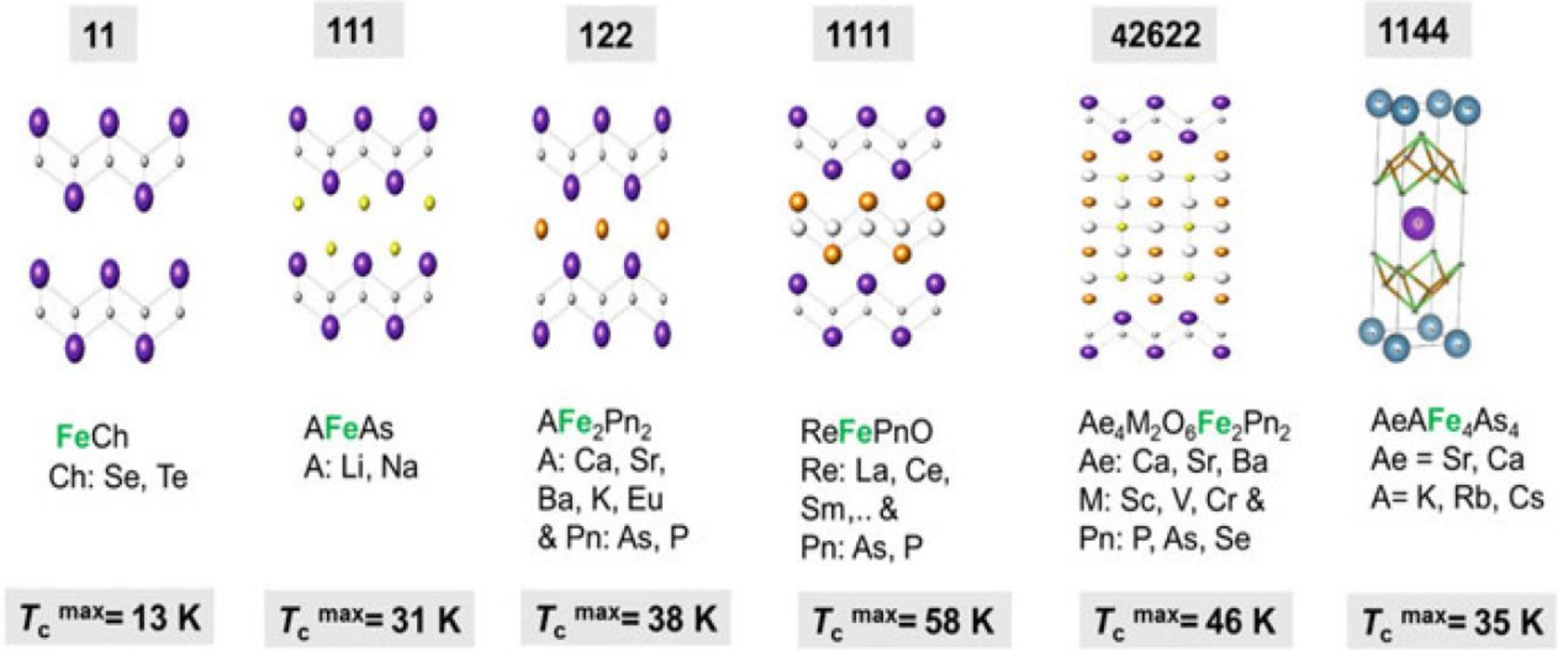
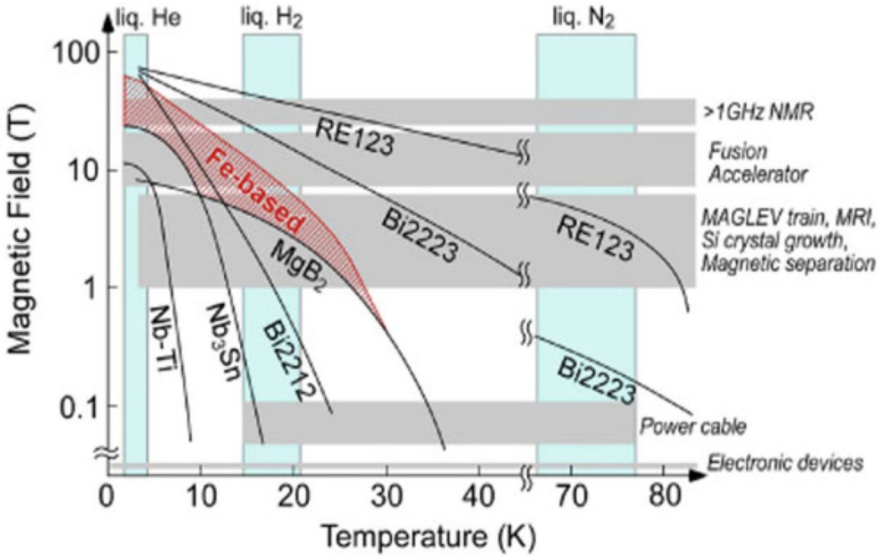
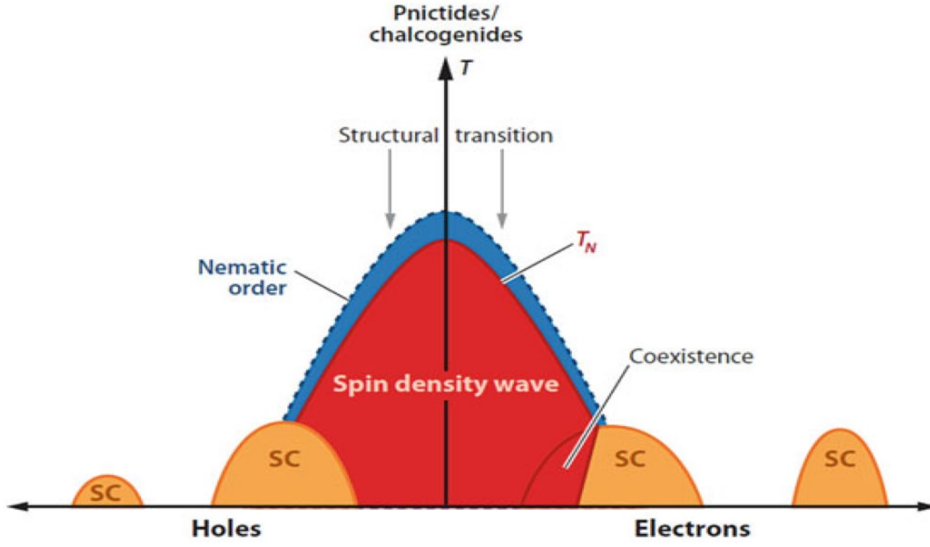
Iron based high T_c superconductors





- ❖ Various FBS Family
- ❖ Magnetic field response of FBS
- ❖ Rich chemistry in FBS

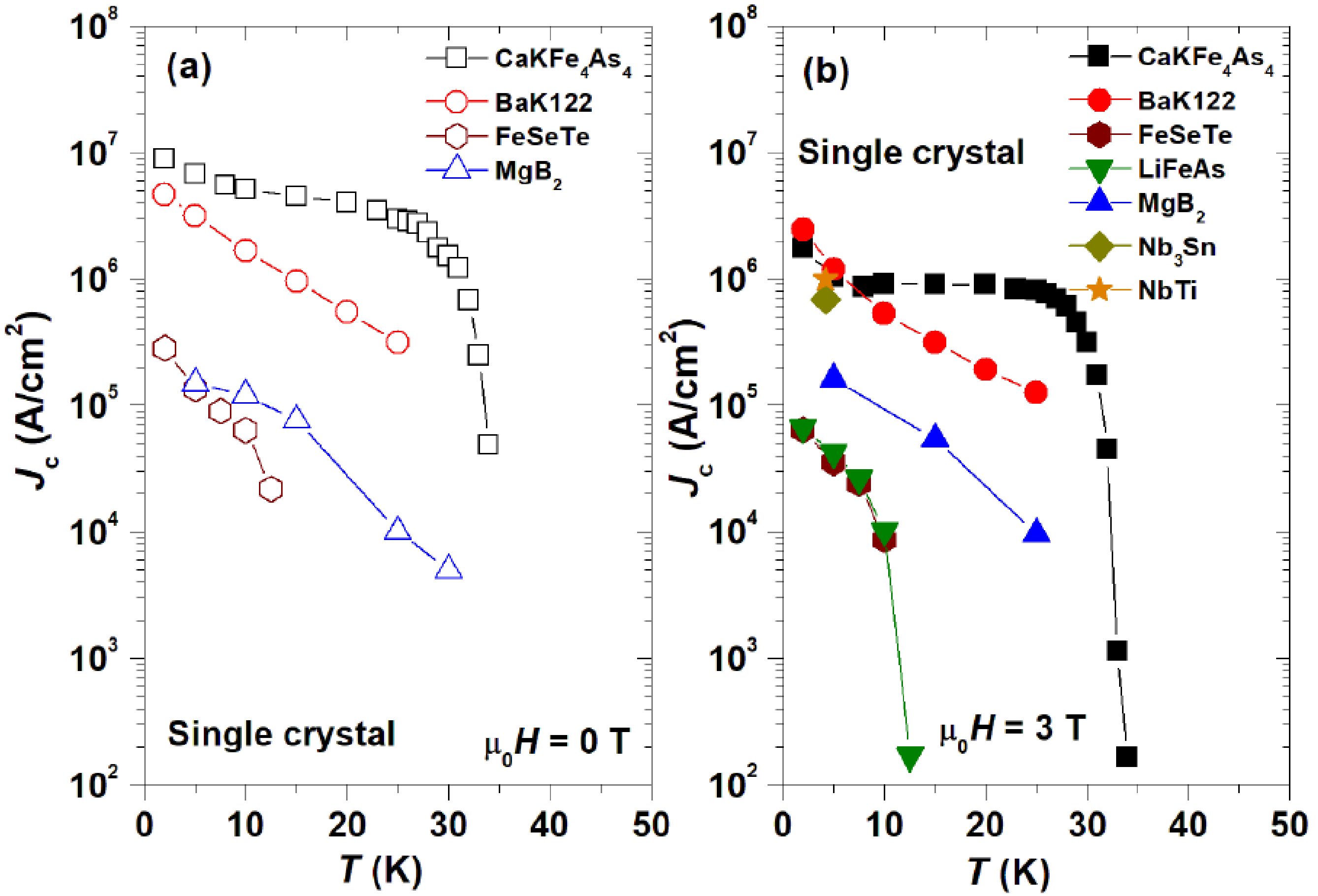


Shiv J. Singh *et. al. Crystals* **12**, 20 (2022).
S. J. Singh *et al. Phys. Rev. Mater.* **2**, 074802 (2018)

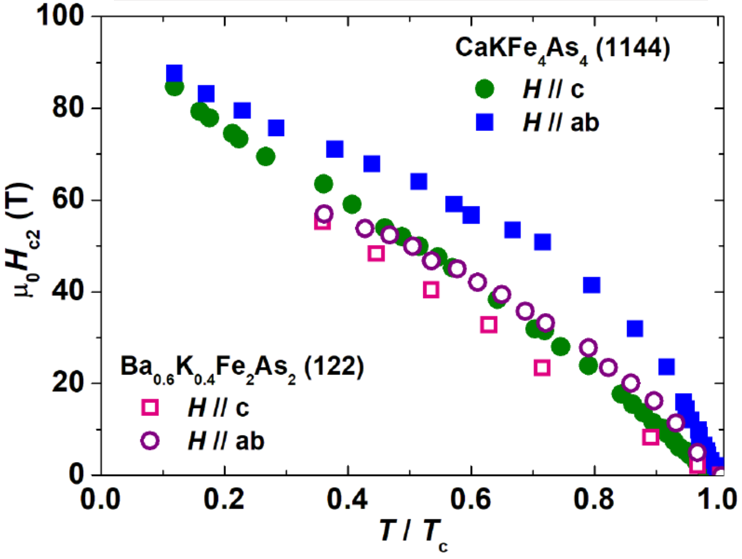
Supercond. Sci. Tech. **27**, 044002 (2014)

Supercond. Sci. Tech. **25**, 113001 (2012)

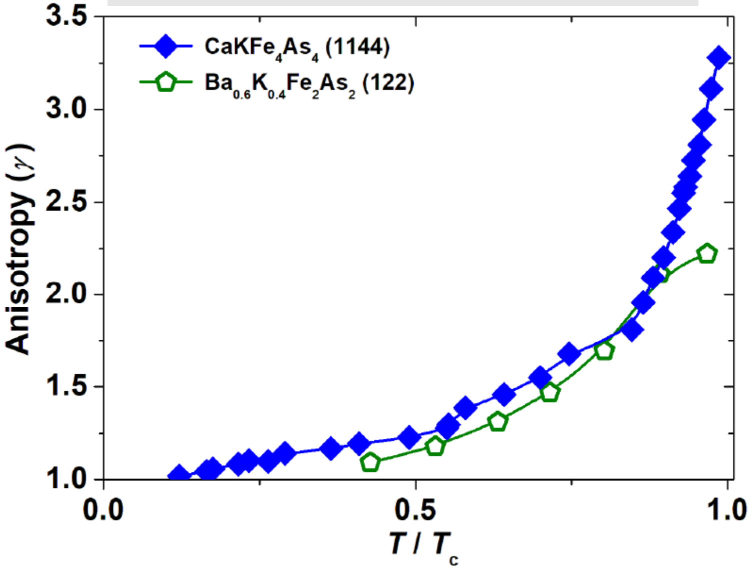
Practical importance of iron-based high T_c superconductors



❖ High upper critical field



❖ Low anisotropy of FBS



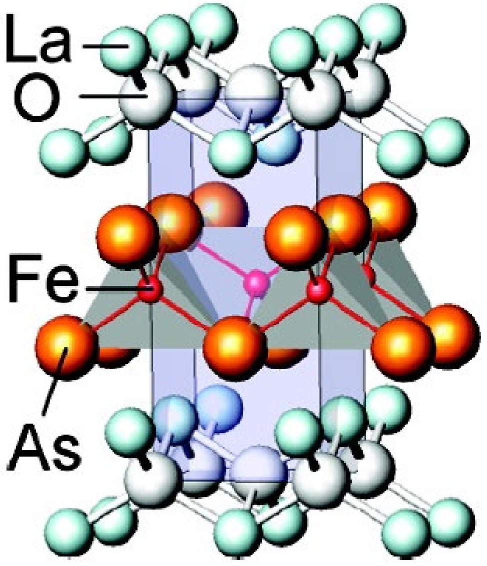
- ❖ High critical current density of 10^7-10^8 A/cm^2
- ❖ High upper field 100 T
- ❖ Low anisotropy ~1-3

S. J. Singh *et al.*, *Jenny Stanford Publishing*: New York, NY, USA, 2021; pp. 283–314. https://doi.org/10.1201/9781003164685

S. J. Singh *et al. Phys. Rev. Mater.* **2**, 074802 (2018).

Two important families of iron based high T_c superconductors

1111



*RE*FeAsO
RE = La, Ce, Sm, Gd

T_c ~ 58 K

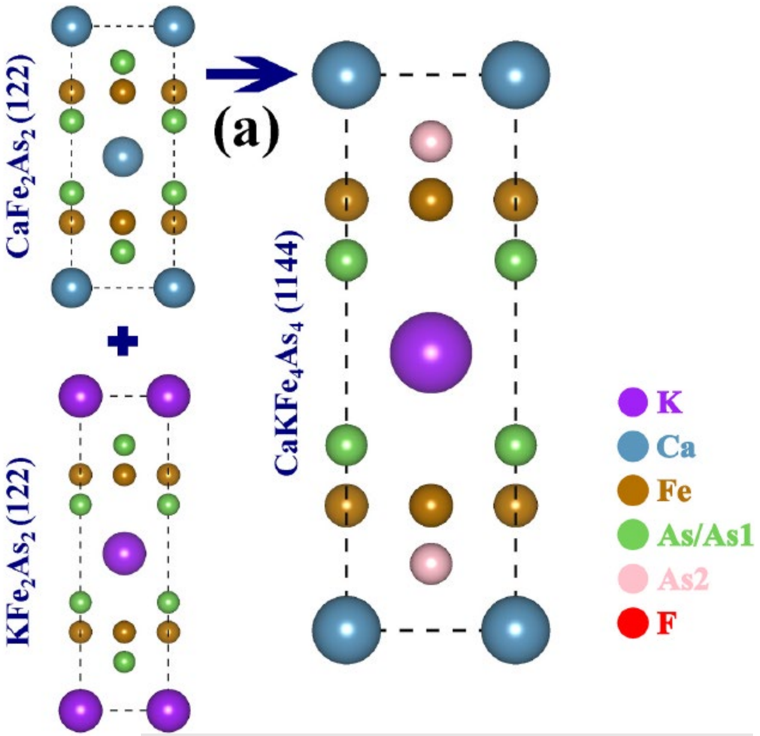
Doped superconductors

- High transition temperature for FBS
- High critical current density for FBS
- High upper critical field

J. Am. Chem. Soc. **130**, 3296 (2008) | *J. Phys. Chem. Solids.* **160**, 110310 (2022)

High pressure growth technique is used to improve the sample quality and superconducting properties

1144



AeAFe$_4$As$_4$
Ae = Ca, Eu and *A* = K, Rb

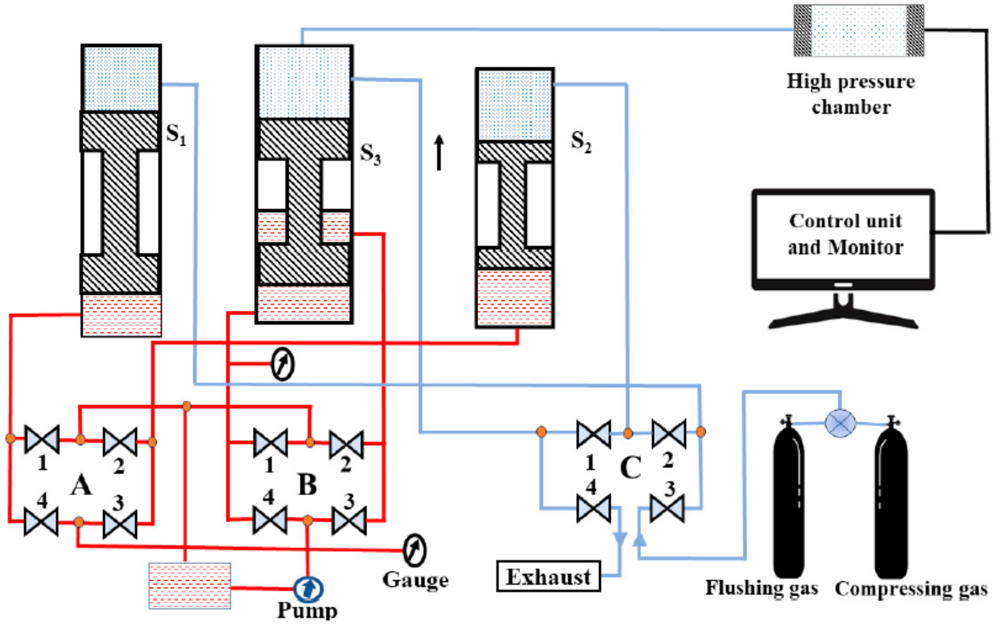
T_c ~33-34 K

Stoichiometric superconductors

- Comparative studies for doped and stoichiometric superconductors

High gas pressure and high-temperature synthesis (HP-HTS) technique

The block diagram



Real pressure chamber

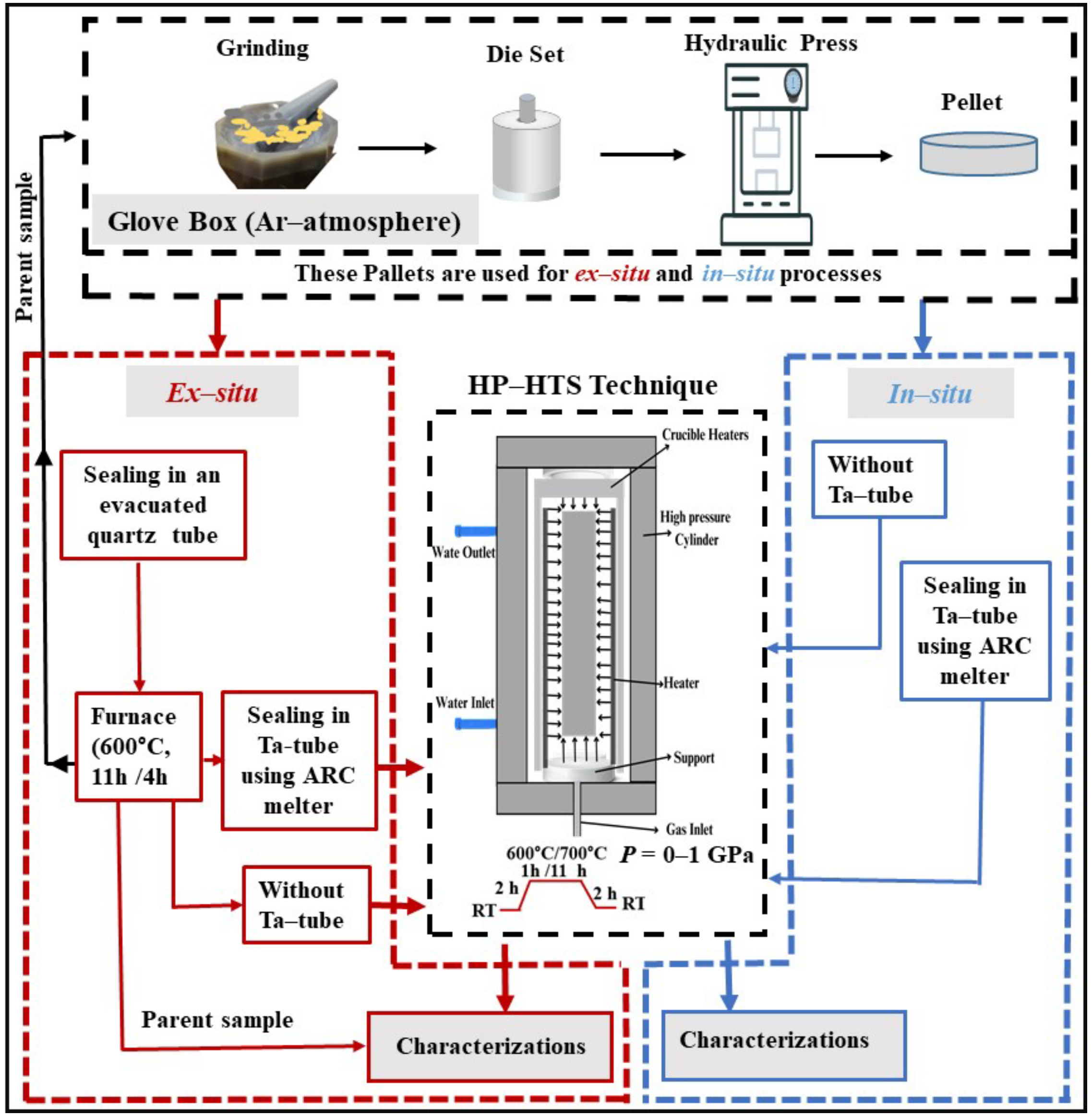
Sample holder

Compressor

Azam *et al. Crystals* **13**(10), 1525 (2023)

High gas pressure: up to 1.8 GPa and
Heating temperature: up to 1700^{o}C

High pressure growth parameters



- Need to optimize various parameters under high pressure growth:
  - Growth pressure (0-1.8 GPa)
  - Heating time
  - In-situ process
  - ex-situ process
  - Sealed in Ta-tube
  - Unsealed in Ta-tube
  - Use of grinding and pelletized or powder

Azam *et al. Materials* **16**(15), 5358 (2023)

- To check reproducibility of each sample, at least two growth has been performed for each batch.

High pressure growth of a doped superconductor

❖ High pressure growth of 1111

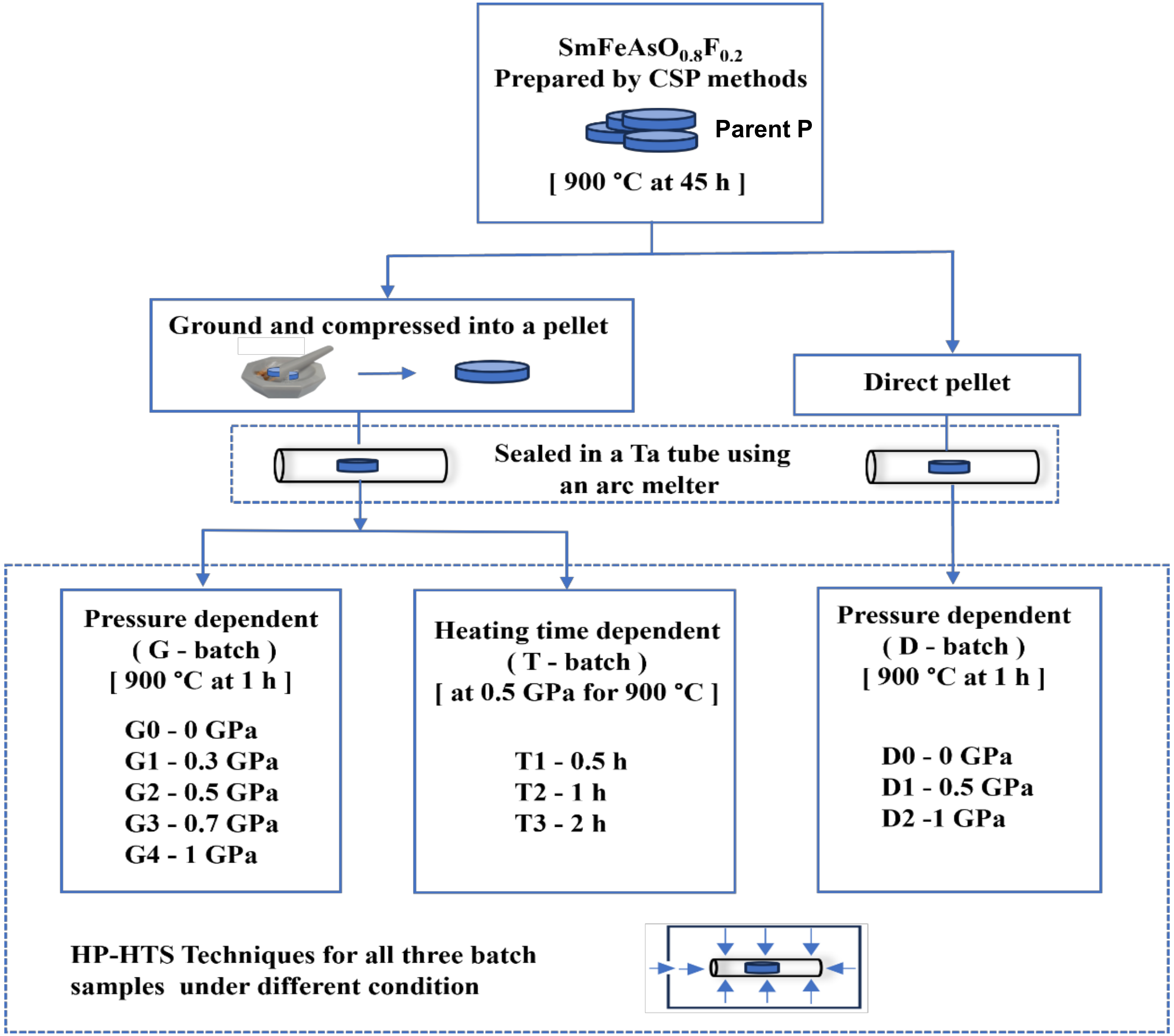
(1111: *RE*FeAsO, *RE* = La, Ce, Sm, Gd)

Azam et al. *et al.* Submitted to journal (under review) (2024)

Azam et al. *et al. IEEE Trans. Appl. Supercond.* **34**, 7300205 (2024)

Azam et al. *et al. J. Am Ceram Soc.* 2024;1–15 (2024)

High pressure growth of F doped SmFeAsO superconductor



- F doped Sm1111 ($SmFeAsO_{0.8}F_{0.2}$) prepared by Conventional Synthesis method at ambient pressure (CSP)
  (Sample P; Transition temperature T_c~53 K)

- Optimization of F doped Sm1111 by the high gas pressure growth of under various growth pressures (0–1.8 GPa).

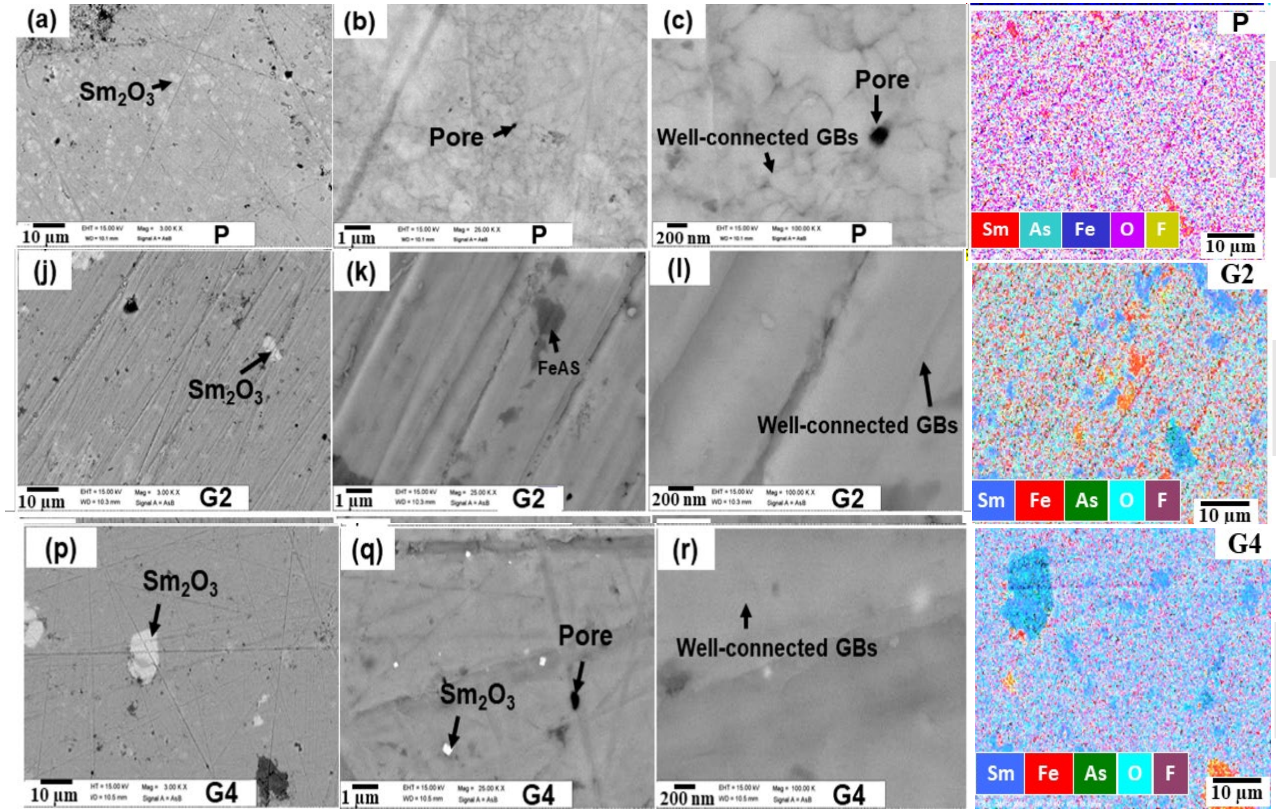
- Grinded and pelletized condition
  Different pressure P: 0-1 GPa ⟶ **G-batch**
  Different heating time t : 0-2 hours ⟶ **T-batch**

and

- Direct pellet of the parent sample P
  Different pressure P: 0-1 GPa ⟶ **D-batch**

Azam et al. *et al.* Submitted to journal (under review) (2024)

High pressure growth of F doped SmFeAsO superconductor



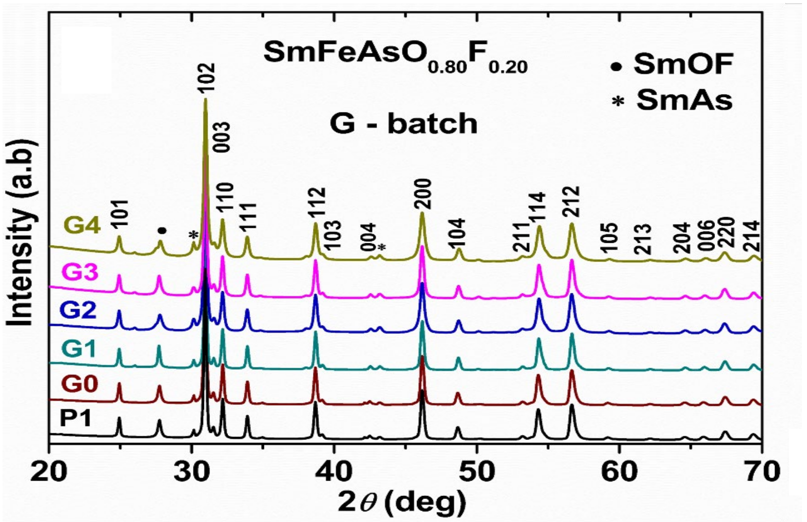
Parent
(P: 0 GPa)

G-batch
G2: 0.5 GPa

G-batch
G4: 1 GPa

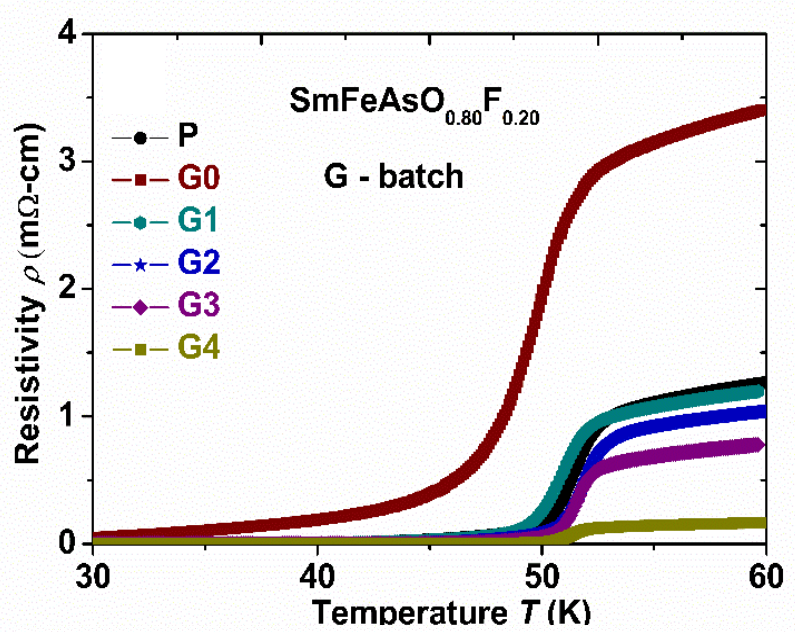
Azam et al. *et al.* Submitted to journal (under review) (2024)

- The impurity phase Sm_2O_3/SmOF are homogeneously distributed for the parent P by CSP. (Sample density ~ 50%)
- The amount of this impurity phase is not changed with HP-HTS but accumulated many area. (Sample density ~ 59%)
- This accumulation is more visible at higher pressure. (Sample density ~ 51%)

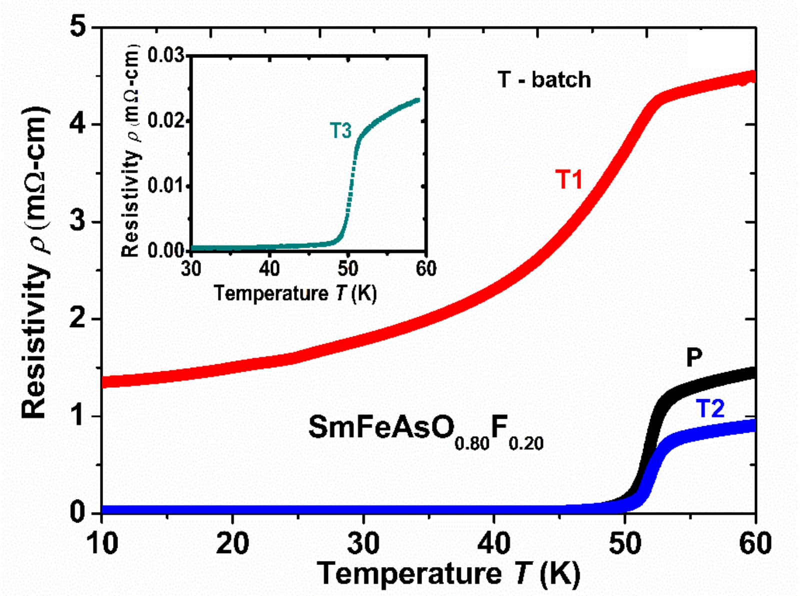


- The amount of the impurity phase is not changed with HP-HTS but accumulates in many areas.

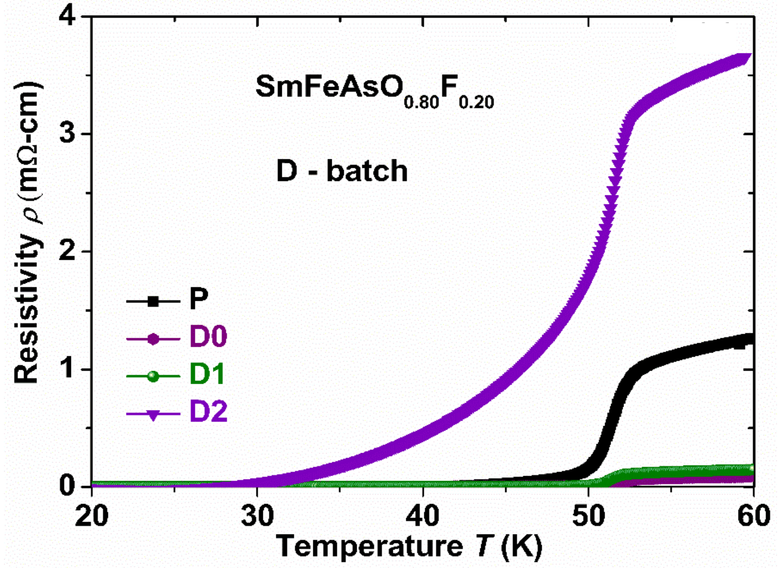
High pressure growth of 1111 superconductor



❖ For G-batch, the T_c^{onset} value is increased by ~1 K for the growth pressure of 0.5 GPa.



❖ For T-batch, the highest T_c^{onset} value is reached for heating time of 1 hour.



❖ For D-batch, a slight variation (~0.5 K) of T_c^{onset} value is observed for different growth pressures.

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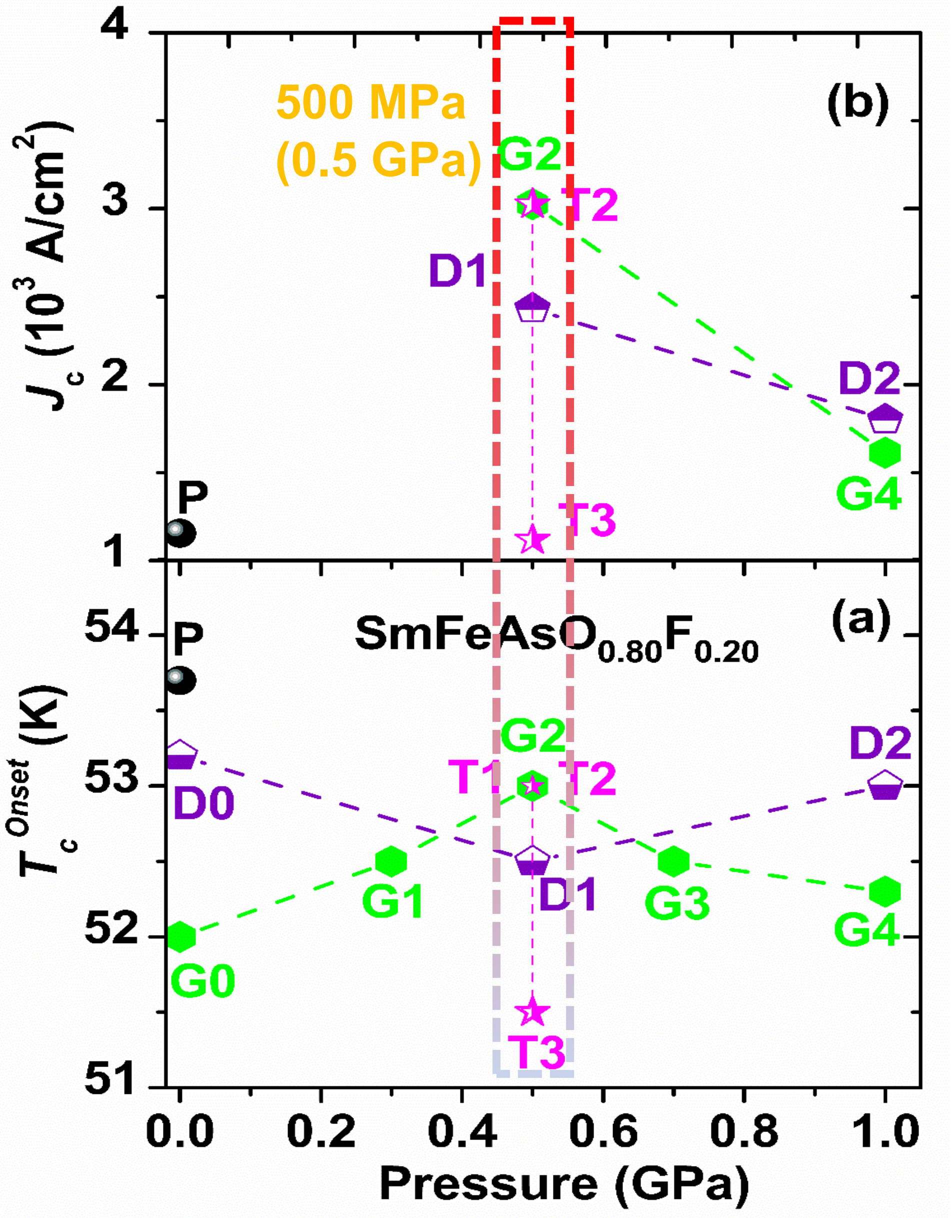
High pressure growth of 1111 superconductor



- Highest T_c^{onset} value for the sample G2 (grinded and pelletized) i..e the growth pressure of 0.5 GPa
- Slightly lower T_c^{onset} for the D1 (direct pellet) prepared at 0.5 GPa
- Long heated sample T3 (Long heating time: 2 h), Lower T_c^{onset} ~51 K
- The samples prepared at 0.5 GPa has shown the high J_c value than the parent P and other samples

Azam et al. *et al.* Submitted to journal (under review) (2024)

- **The optimal growth pressure: 0.5 GPa, 900°C, 1 h**

  Grinded and pelletized parent P

High pressure growth of the stoichiometric compound

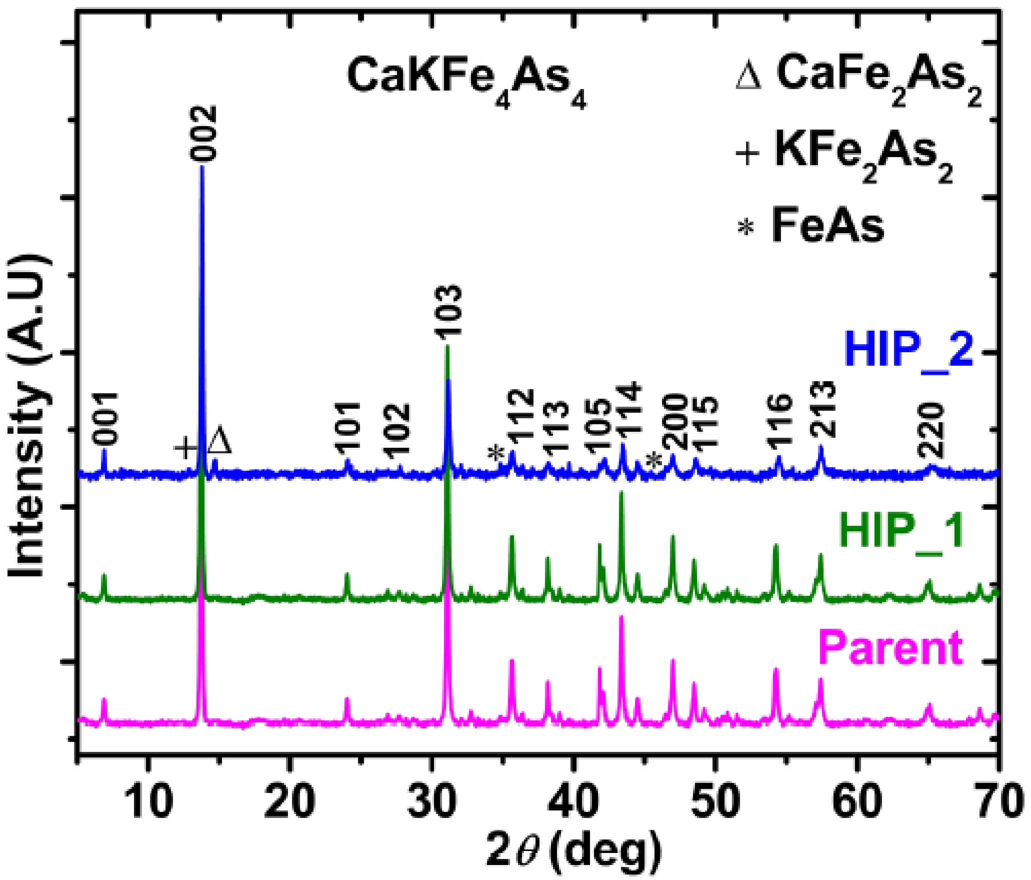
❖ **High pressure growth of 1144: $CaKFe_4As_4$**

Manasa et al. *IEEE Trans. Appl. Supercond.* **34**, 7300605 (2024)

Manasa *et al. Ceramics International* **50**, 714-72 (2024)

Manasa *et al. J. Phys. Chem. Solids.* **190**, 111996 (2024)

High pressure growth of stoichiometric 1144 superconductor

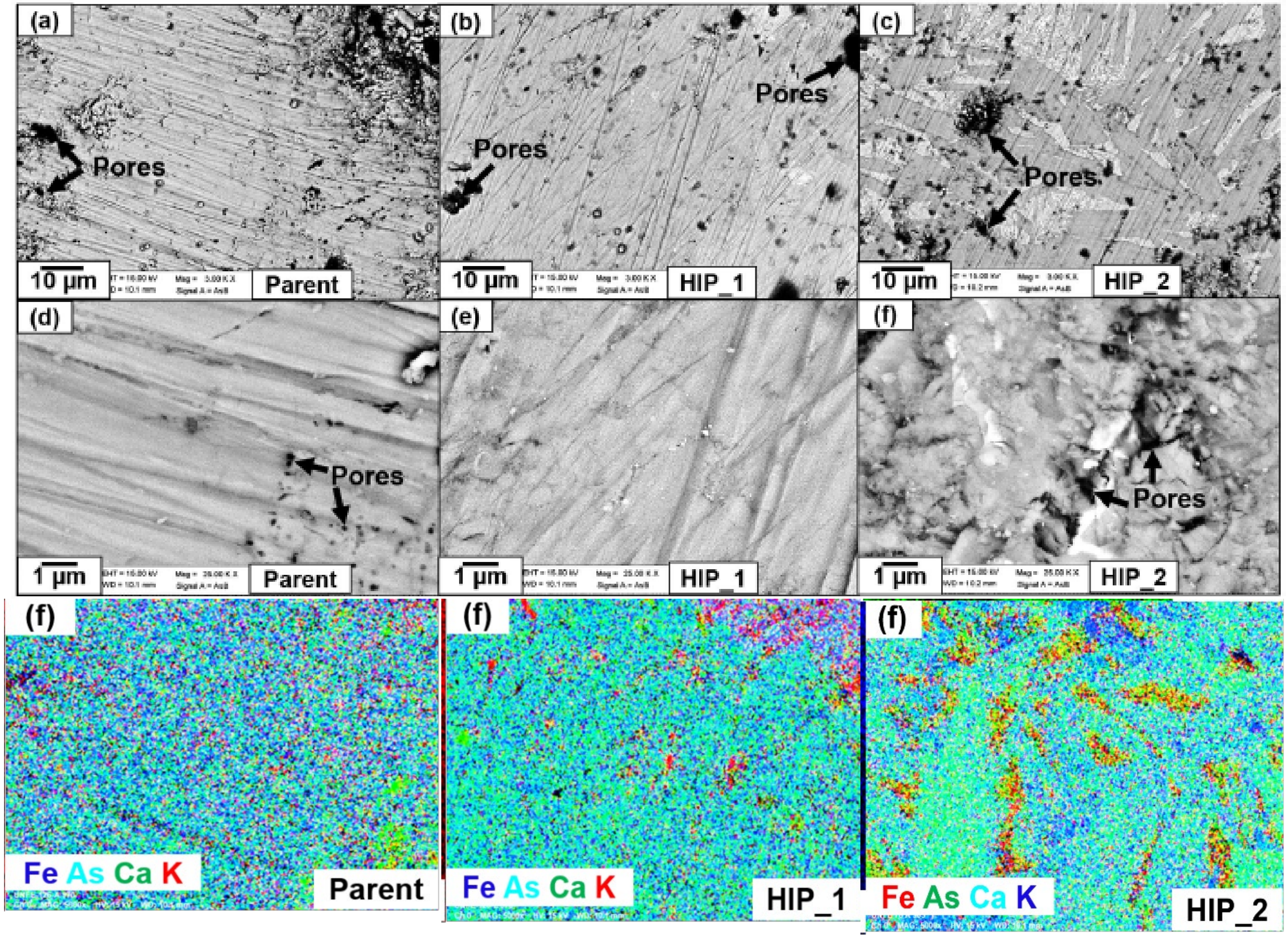


- **Parent: 0 GPa**
  HIP_1: 500 MPa (open in Ta-tube)
  HIP_2: 500 MPa, 1 h (sealed in Ta-tube)
- XRD analysis confirms the tetragonal phase with space group *I4/mmm* ($ThCr_2Si_2$-type structure)
- **Parent and HIP_1 have a clean 1144 phase** and no impurity phase was observed.
- A small amount of $CaFe_2As_2$ is detected together with a tiny amount of FeAs for HIP_2.

Manasa *et al. J. Phys. Chem. Solids.* **190**, 111996 (2024)

Manasa *et al. IEEE Trans. Appl. Supercond.* **34**, 7300605 (2024)

High pressure growth of stoichiometric 1144 superconductor



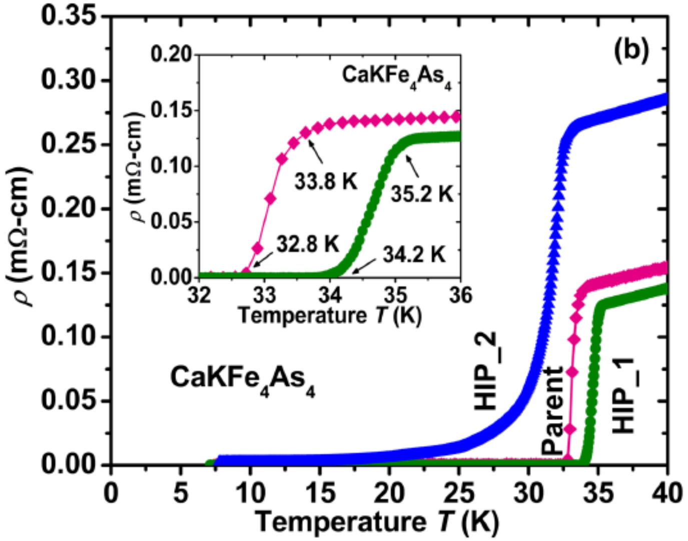
- The parent and HIP_1 have almost homogeneous microstructures.
- It seems that HIP_1 has many well-connected grain boundaries (GBs) and is more compact compared to the parent compound.
- However, many pores do exist in the parent compared to HIP_1.

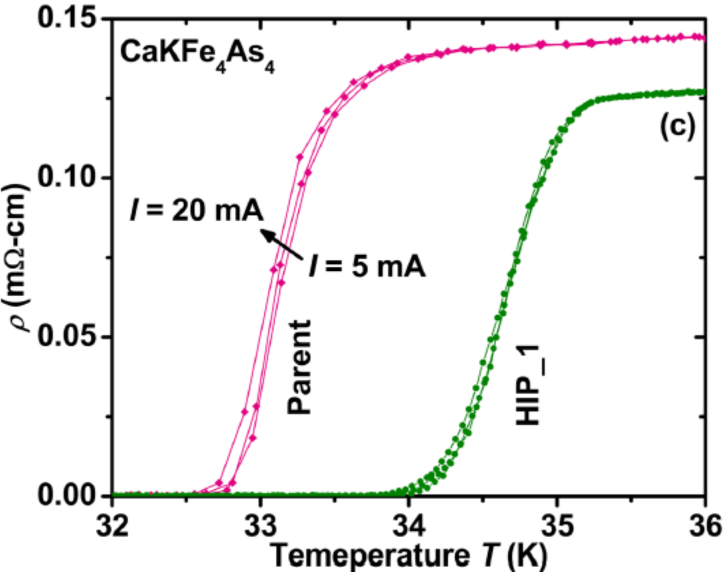
Manasa *et al. J. Phys. Chem. Solids.* **190**, 111996 (2024)

- In the case of HIP_2, it appears that grain connections are reduced rapidly and pore sizes are increased

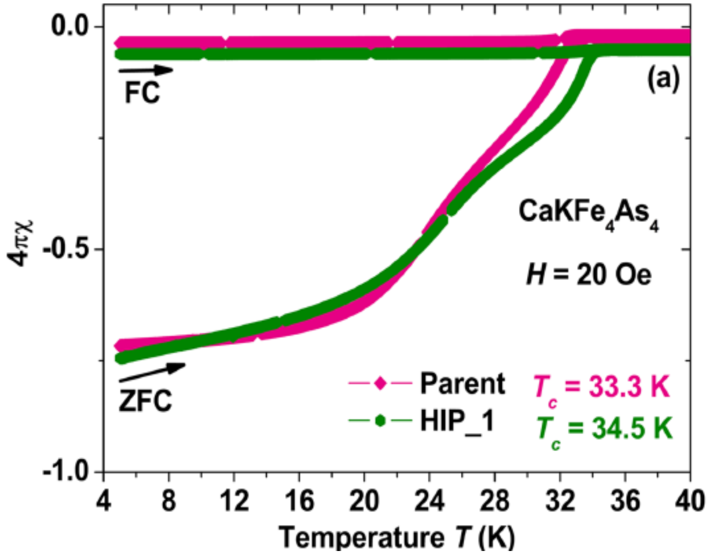
Manasa *et al. IEEE Trans. Appl. Supercond.* **34**, 7300605 (2024)

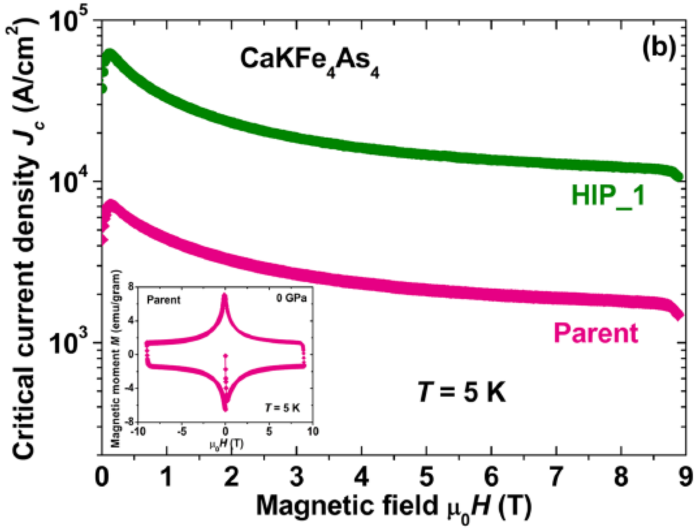
High pressure growth of stoichiometric 1144 superconductor





- The parent compound: T_c^{onset} **= 33.8 K with Δ*T*~1K**
- **HIP_1 sample:** T_c^{onset} **= 35.2 K with Δ*T*~1K** comparable to that of 1144 single crystal.
- The sharper transition suggest better grain connections.
- By the high-pressure synthesis method, the J_c **value is enhanced by one order of magnitude compared to the parent sample.**





Manasa *et al. J. Phys. Chem. Solids.* **190**, 111996 (2024)

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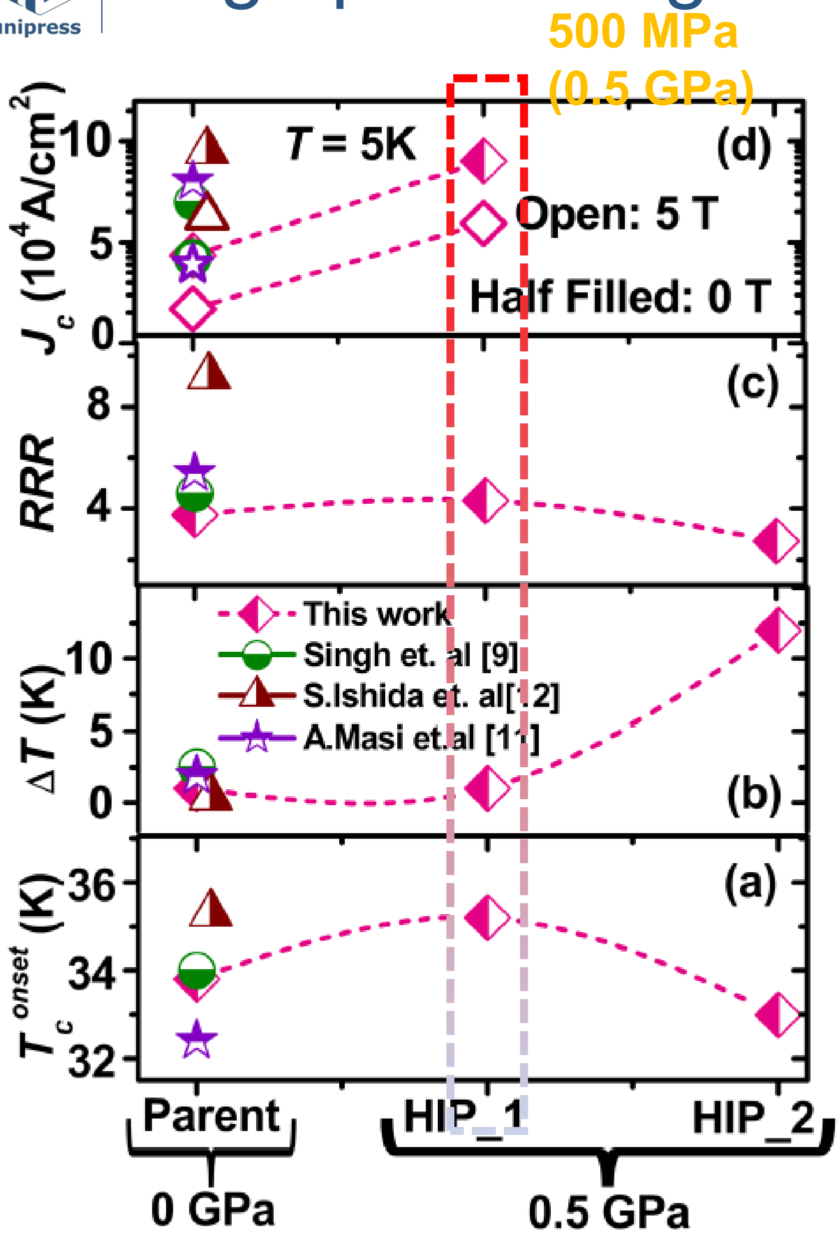
High pressure growth of stoichiometric 1144 superconductor



- HIP_1 has a slightly improved *RRR* value (4.3) than that (3.7) of the parent sample, suggesting a homogeneous and good-quality of HIP_1 sample compared to our other samples.
- Interestingly, HIP_1 has enhanced the J_c value in the whole magnetic field up to 9 T compared to the parent samples.

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- This value is almost the same as a value reported for 1144 prepared by CSP [9] [11] at ambient pressure and SPS [12].
- **$CaKFe_4As_4$ prepared at 0.5 GPa by HP-HTS into an open Ta-tube exhibits high superconducting properties with the improved sample quality.**
- **Our study confirm that high-pressure synthesis has worked well for the 1144 family.**

Manasa *et al. IEEE Trans. Appl. Supercond.* **34**, 7300605 (2024)

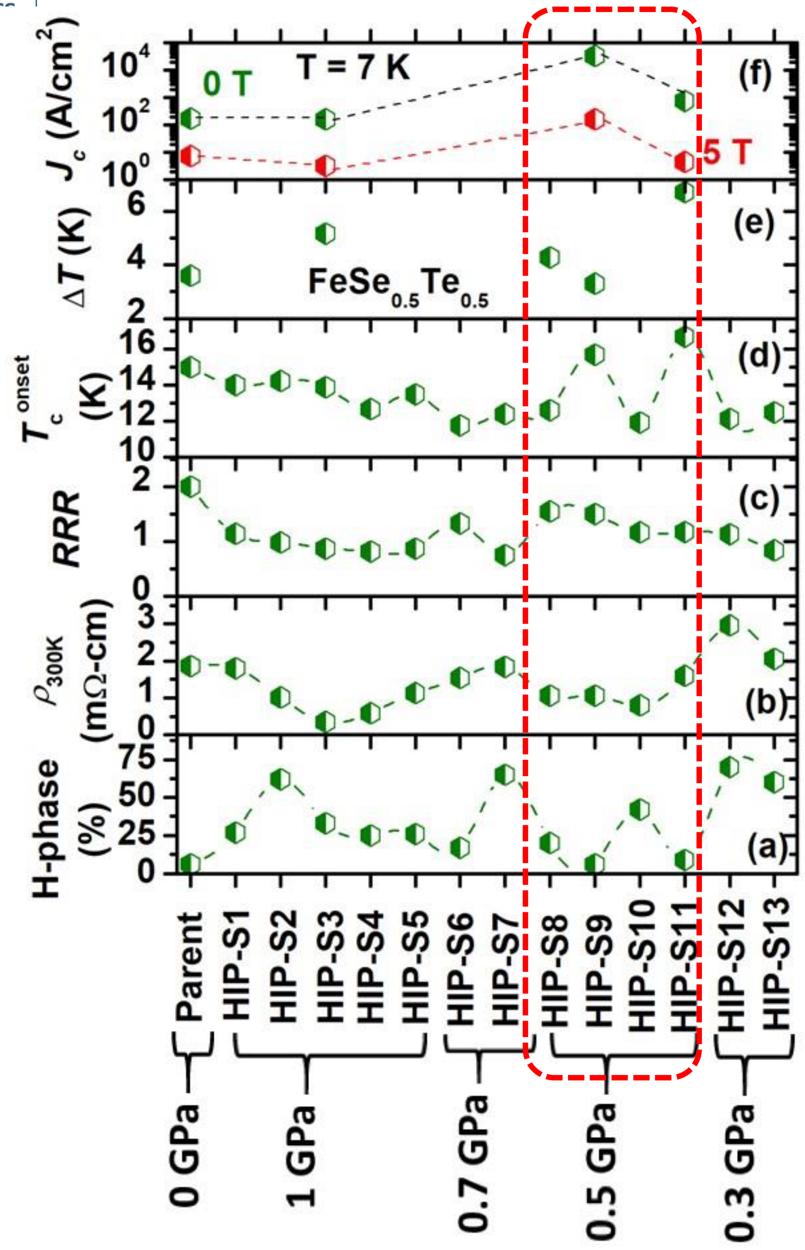
High pressure growth of the simplest FBS

❖ High pressure growth of Fe(Se,Te) (11) family

Manasa *et al. Ceramics International* **50**, 714-72 (2024)

Azam *et al. Materials* **16**(15), 5358 (2023)

High pressure growth of $FeSe_{0.5}Te_{0.5}$ by HP-HTS



- Hexagonal phase reached its lowest level for the samples prepared at 500 MPa for 1 h with sealing into a Ta-tube.
- **$FeSe_{0.5}Te_{0.5}$ sample sealed into a Ta-tube** is more effective for the enhancement of sample density and the improvement in grain connectivity.
- Although the existence of a hexagonal phase depending on the pressure synthesis conditions reduces the superconducting grain connections.

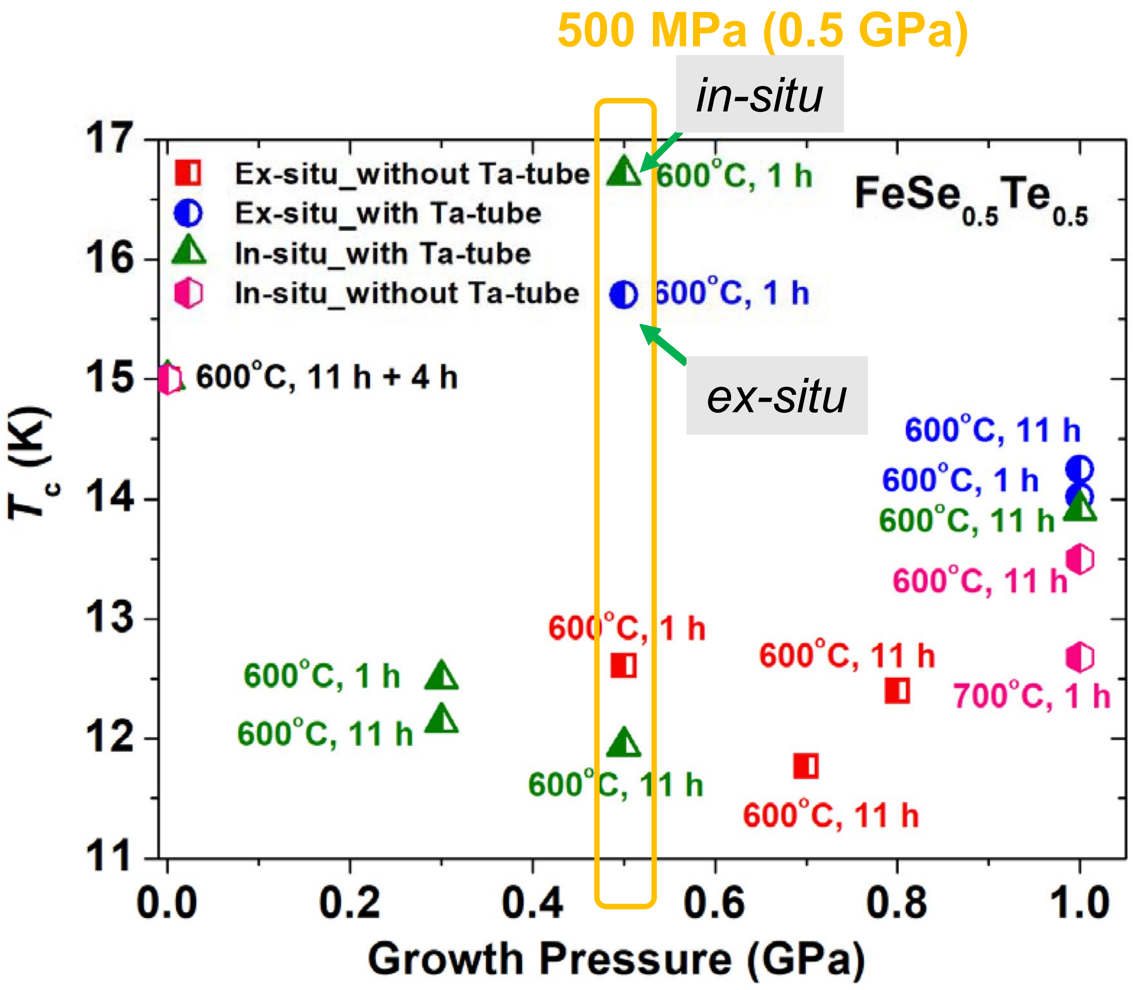
Manasa *et al. Ceramics International* **50**, 714-72 (2024)

Editor's Choice

M. Azam, M. Manasa, T. Zajarniuk, R. Diduszko, T. Cetner, A. Morawski, A. Wiśniewski, S. J. Singh, *Materials* **16**(15), 5358 (2023)

S. J. Singh *et al.. Appl. Phys. A* **128**, 476 (2022)

11 family: $FeSe_{0.5}Te_{0.5}$ by HP-HTS



- The enhancement of the transition temperature by 2 K for $FeSe_{0.5}Te_{0.5}$ prepared at 500 MPa.
- **Optimum high-pressure growth conditions are 500 MPa, 600°C, a heating time of 1 h**, and the sample sealed in a Ta-tube,
- ***In-situ* process: sufficient for the development of the tetragonal phase formation**, and
- ***Ex-situ* process: contributes to the improvement in the intergrain connections and also promotes the formation of the superconducting phase.**

Manasa *et al. Ceramics International* **50**, 714-72 (2024)

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Materials **16**(15), 5358 (2023)

Summary

- High pressure synthesis is an effective way to enhance the sample quality and superconducting properties of high T_c iron based superconductors.

- **The high-pressure synthesis of these samples has enhanced the T_c by 2-3 K for $CaKFe_4As_4$ and Fe(Se,Te) bulks, whereas it is almost constant for the 1111 family.**

- The sample quality, sample density, and grain connections of all these FBS families have improved, and their J_c value has increased by one order of magnitude (10^4-10^5 A/cm^2, 5 K, 0 T) compared to that of CSP (10^2-10^3 A/cm^2, 5 K, 0 T).

- A growth pressure of 0.5 GPa and a short heating time (~1 hour) are sufficient and work well as optimal conditions for various families of FBS.

- **High-pressure growth works well for various FBS, and more research is demanded in this direction.**

Acknowledgment

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Thank you very much for your attention