MICROWAVE RESPONSE, COMPLEX CONDUCTIVITY AND EFFECT OF ORDER PARAMETER SYMMETRY IN Fe-BASED SUPERCONDUCTORS

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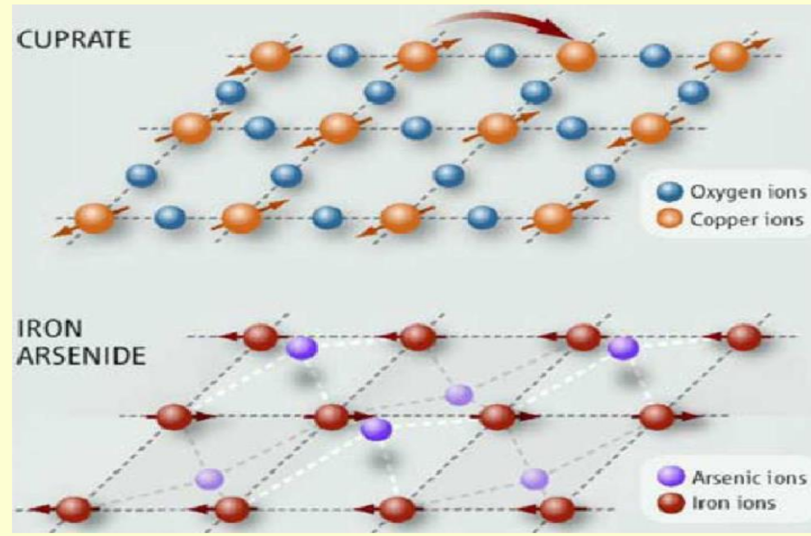
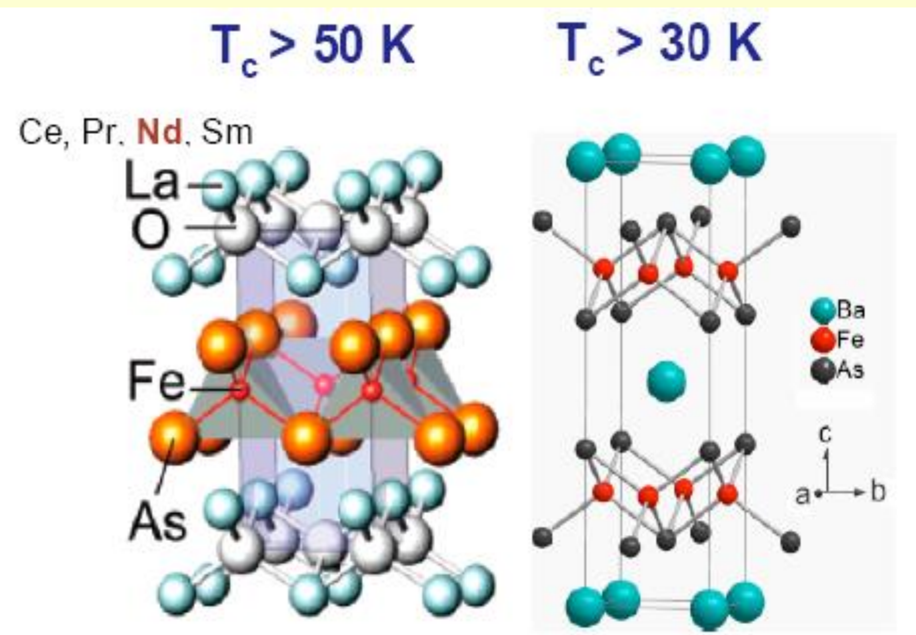
Contents:

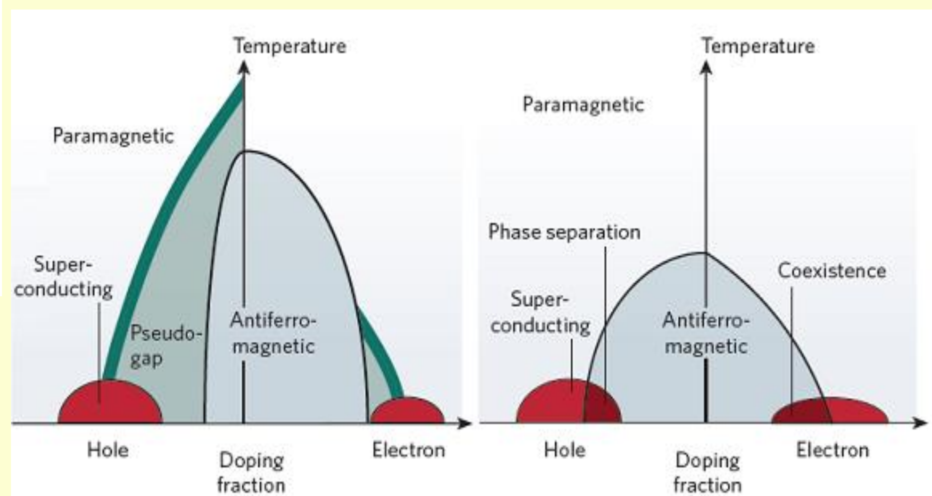
1. Introduction. Measurement techniques regarding the wave symmetry in Fe-SCs.

Y. Kamihara, H. Hiramatsu, M. Hirano, R. Kawamura, H. Yanagi, T. Kamiya, H. Hosono
J. Am. Chem. Soc. 128, 10012 (2006)
T. Watanabe, H. Yanagi, T. Kamiya, Y. Kamihara, H. Hiramatsu, M. Hirano, H. Hosono
Inorg. Chem. 46, 7719 (2006)
LaOFeP with Tc = 5K, LaONiP Tc = 3K
It has not attracted much attention from HTS community

Y. Kamihara, T. Watanabe, M. Hirano, H. Hosono. *J. Am. Chem. Soc.* 130, 3296 (2008)
Discovery of $LaO_{1-x}F_xFeAs$ (x = 0.05 − 0.12), Tc = 26K
R. Zhi-An et al., *Chin. Phys. Lett*. 25, 2215 (2008).
$SmFeAs(O_{1-x}F_x)$, Tc>50K *Situation has changed sharply!*







2008: "The end of the tyranny of copper" (P.C.Canfield)

Understanding the pairing mechanism and origin of the superconductivity in any new superconductor ⇒
⇒*Requiring various experimental techniques*

A full mutual agreement on physical finding

Groups of measurements

Flux quantization; Phase coherence measurements	**Spectroscopy: tunneling, IR, MW, ARPES**	**Temperature dependence of thermal or electromagnetic properties**

2. MW surface impedance. Complex conductivity. Two high-Q resonator techniques.

From experiment: $Q(T)$, $\Delta f\ (T)$, $\lambda(0)$-*as a rule from another experiment*

$$Z_s = \sqrt{\frac{i\omega\mu_0}{\sigma_1 - i\sigma_2}} = R_S + iX_S$$

$\sigma=\sigma_1 - i\sigma_2$, $\sigma_1=2\omega\mu_0 R_s X_s/(R_s^2+X_s^2)^2$, $\sigma_2=\omega\mu_0(X_s^2-R_s^2)/(R_s^2+X_s^2)^2$

$\sigma_1=\sigma_n$, $\sigma_2=1/(\omega\mu_0\lambda^2)=-i\sigma_s$

Both Drude formula validity and equality $n_s(0)-n_s(T)=n_n(T)$ allows obtaining:

$$\tau^{-1}(T)=\frac{1-\dfrac{\lambda^2(0)}{\lambda^2(T)}}{\mu_0\sigma_1(T)\lambda^2(0)},\omega\tau<<1;\qquad \tau^{-1}=\frac{1}{\mu_0\sigma_1{}'(T)\lambda_L^2(0)}-\omega\frac{X_S^2-R_S^2}{2X_S R_S}$$

Two measurement techniques

I). Ka-band (35 – 40 GHz range), sapphire QDR with CEP: *N. Cherpak, A. Barannik, Y. Filipov, Y. Prokopenko and S. Vitusevich*, *IEEE Trans. Appl. Supercond. 13, 3570 (2003).*
Millimeter-Wave Surface Impedance Characterization of HTS Films and Single Crystals Using Quasi-Optical Sapphire Resonators: *N.Cherpak, A.A.Barannik, S.A.Bunyaev, Yu.V.Prokopenko. K.I.Torokhtii, and S.A.Vitusevich*, *IEEE Appl. Supercond.,Vol.21, No 2 (2011).*

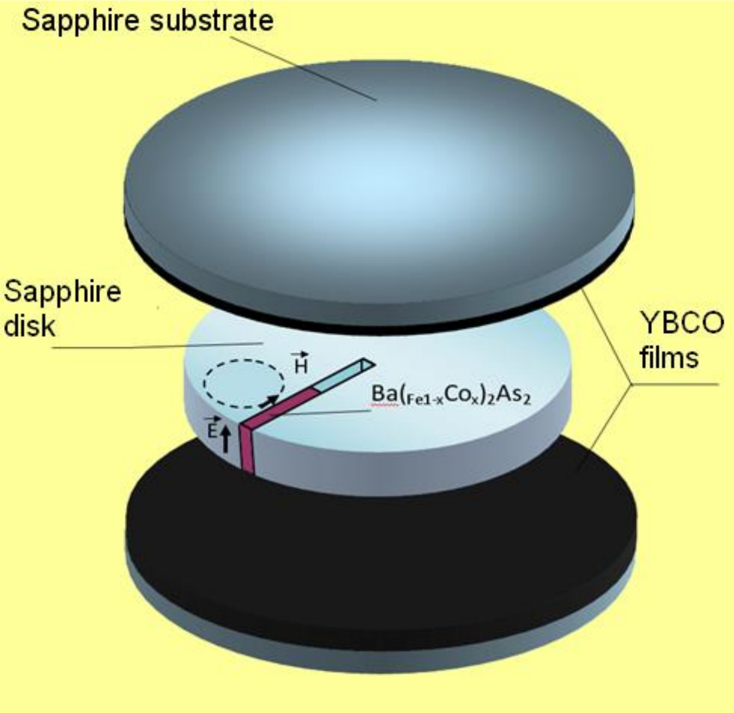


Figure 1. The slotted sapphire disk resonator with a single crystal $Ba(Fe_{1-x}Co_x)_2As_2$ in a slot.

Advantages: mm wavelength range,
$Q \cong 10^5$ (T_{LHe} - 30 K)

The technique allows carrying out study of unconventional SCs using *mm* and *submm* waves.

We studied:

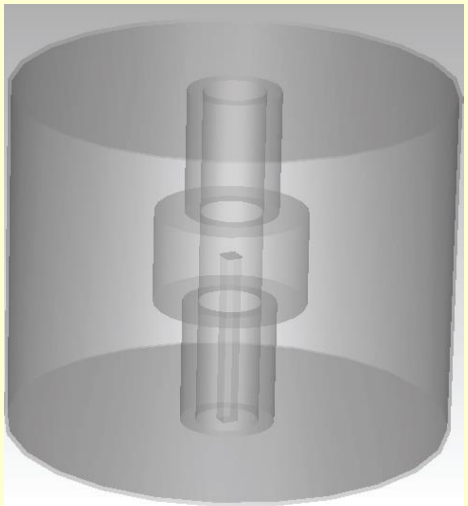
Nb (*testing the technique*)

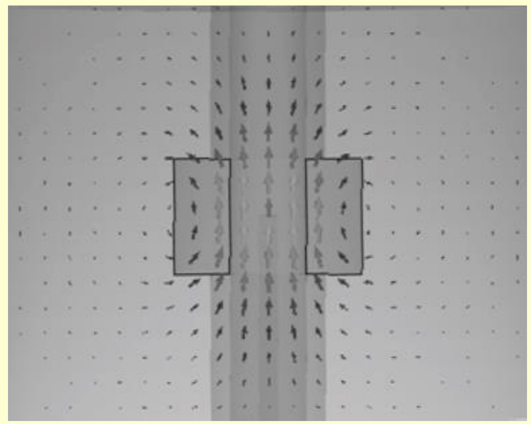
$Ba(Fe_{1-x}Co_x)_2As_2$ (*processed*)

$Ba(Fe_{1-x}Ni_x)_2As_2$ (*unprocessed*)

Two measurement techniques

II). X-band (9 – 11 GHz range), "hot finger" sapphire resonator: *Y. Wu, S. Y. Zhou, X. Y. Wang, L. X. Cao, X. Q. Zhang, S. Luo, Y. S. He, A. A. Barannik, N. T. Cherpak, V. N. Skresanov, IEEE Trans. Appl. Supercond, 21, 599 (2011).*





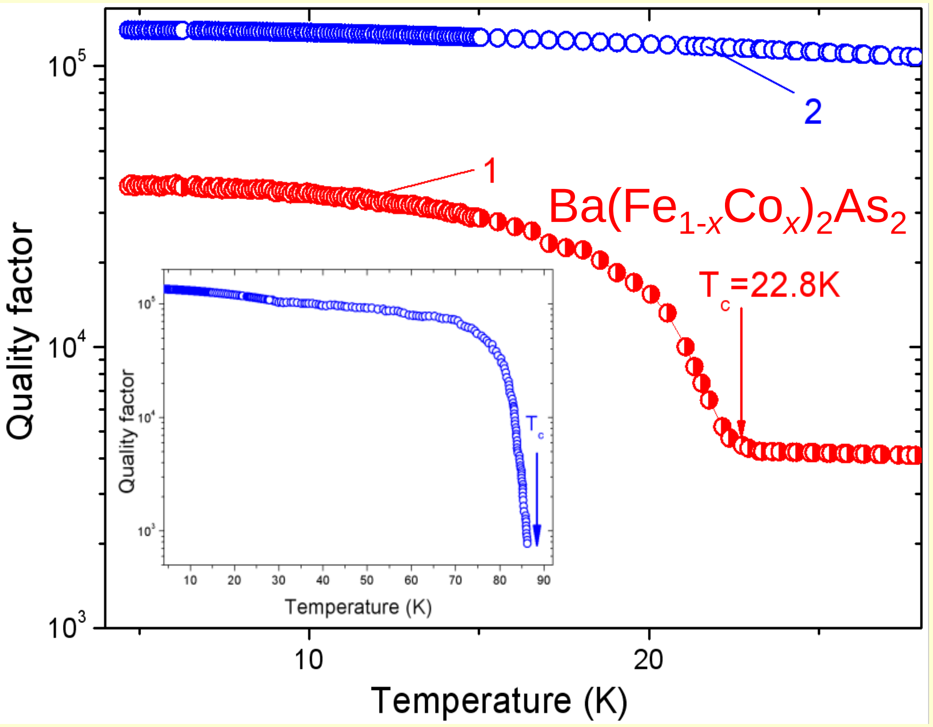
Avantages:
$Q \cong 4.5 \times 10^4$ (RT)
The technique allows carrying out study of small unconventional SCs
We studied:
- $FeSe_{0.3}Te_{0.7}$ thin film
- $BaFe_{2-x}Ni_xAs_2$ single crystal

Figure 2. The "hot finger" sapphire resonator operating in the TE011 mode and MW field configuration. Microwave field is perpendicular to a-b plane of the sample

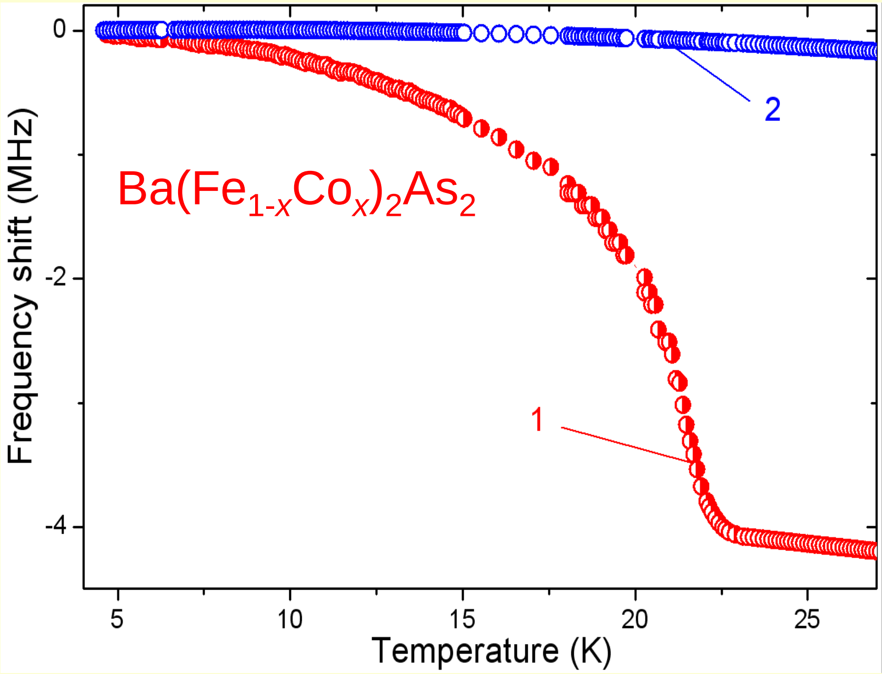
$$R_s^{eff} = \frac{1}{2} R_s \left(\coth\left(\frac{d_f}{\lambda_L}\right) + \frac{d_f}{2\lambda_L} \cos ec^2\left(\frac{d_f}{2\lambda_L}\right)\right)$$

$$X_s^{eff} = \frac{1}{2} X_s \coth\left(\frac{d_f}{2\lambda_L}\right)$$

3. Temperature variation of complex conductivity and penetration depth in $Ba(Fe_{1-x}Co_x)_2As_2$ and $FeSe_{0.3}Te_{0.7}$. Wave symmetry effect.

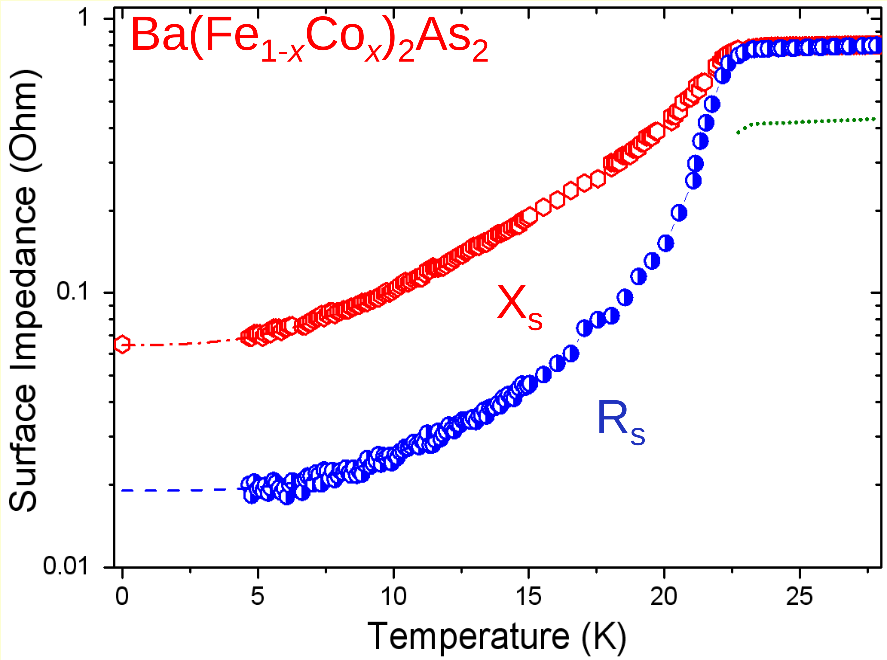


a)



b)

Figure 3. The quality factor (a) and the resonant frequency shift (b) of the resonator with and without single crystal $Ba(Fe_{1-x}Co_x)_2As_2$ sample depending on temperature; 1 - *Q* and frequency shift of the resonator with the sample and 2 - the same without the sample. Insert in Figure 1a shows *Q(T)* of the resonator in temperature interval up to T_c=90K for $YBa_2Cu_3O_{7-\delta}$ film endplates (without the studied sample).



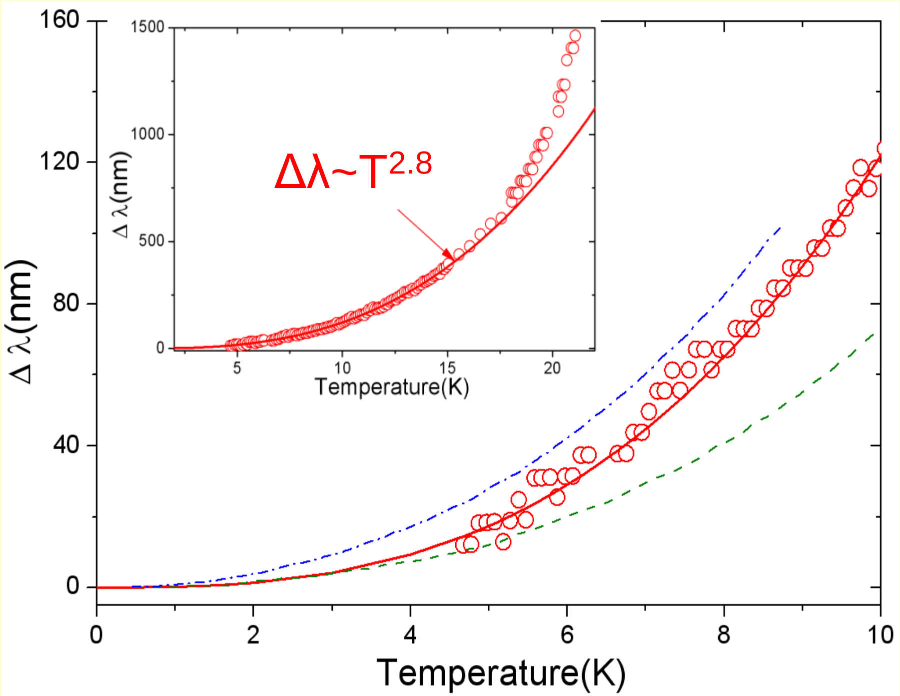


Figure 4. Temperature dependence of the surface impedance of the single crystal $Ba(Fe_{1-x}Co_x)_2As_2$, $R_{res}=R_s(T=0)=19 m\Omega$.

Figure 5. Penetration depth $\lambda(T)$ in single crystal $Ba(Fe_{1-x}Co_x)_2As_2$. The solid line refers to power law $CT^{2.8}$, n = 2.8.

- A. Barannik, N. T. Cherpak, M. A. Tanatar, S. Vitusevich, V. Skresanov, P. C. Canfield, and R. Prozorov, Phys. Rev. B 87, 014506 (2013).

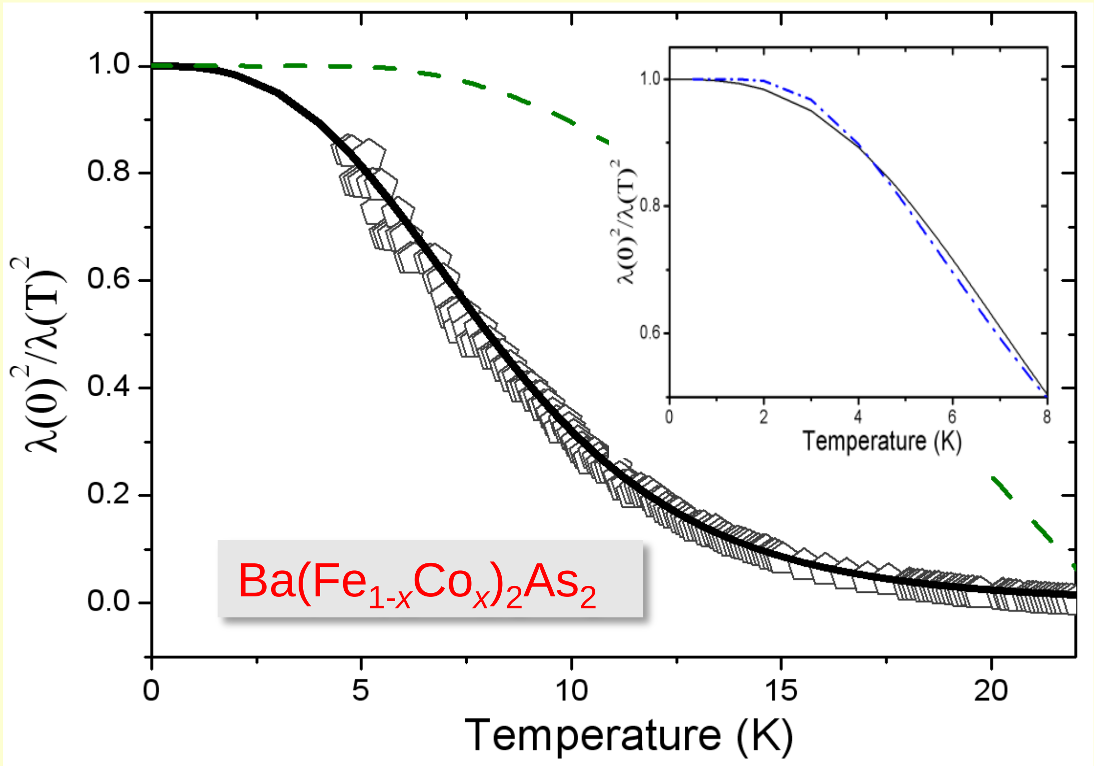


Figure 6. *σ2(T)* in a single crystal $Ba(Fe_{1-x}Co_x)_2As_2$. The solid lines correspond to the power low $T^{2.8}$ A dushed line corresponds to a classic BCS SC with Δ=1.76. Inset shows the power law $\Delta\lambda(T) \sim T^{2.8}$ (solid line) and exponential law with a small Δ=0.75 (dush-and-dotted line) at low *T*.

- Hideyuki Takahashi, Yoshinori Imai, Seiki Komiya, Ichiro Tsukada, and Atsutaka Maeda, *Phys. Rev.* B 84, 132503 (2011). ⇐$FeSe_{0.4}Te_{0.6}$
- Y. Wu, S. Y. Zhou, X. Y. Wang, L. X. Cao, X. Q. Zhang, S. Luo, Y. S. He, A. A. Barannik, N. T. Cherpak, V. N. Skresanov, *IEEE Trans. Appl. Supercond*, 21, 599 (2011). ⇐$FeSe_{0.3}Te_{0.7}$

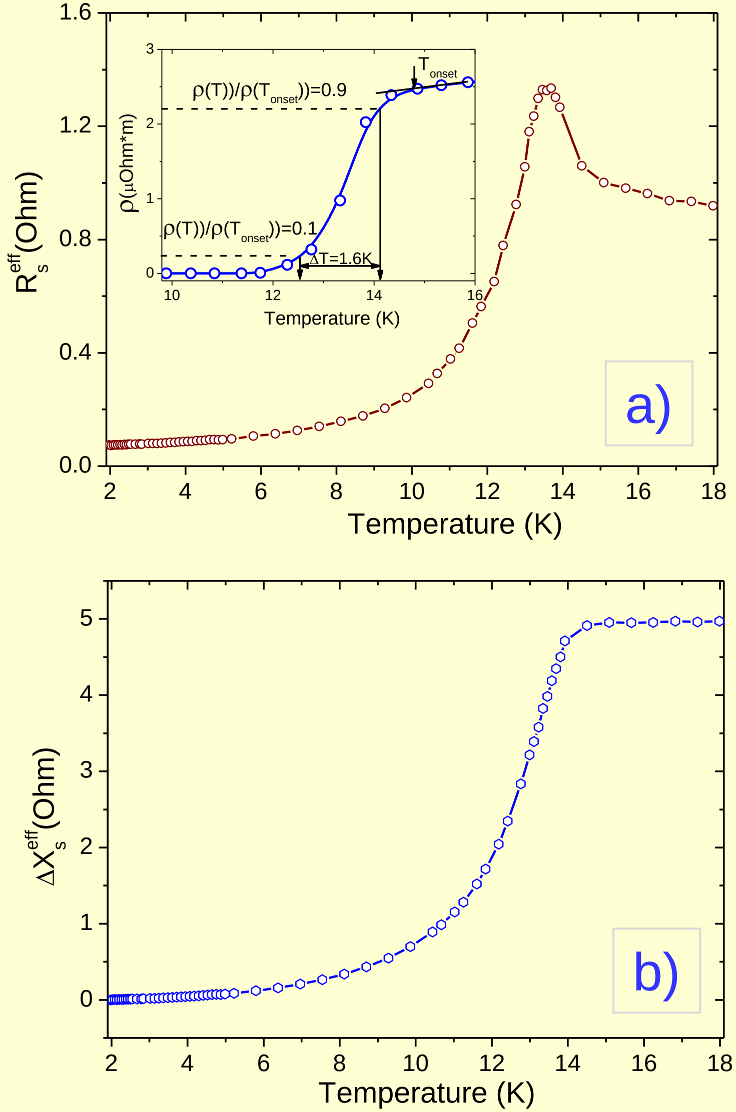


Figure 7. (a) The effective surface resistance Rseff and (b) change of surface reactance ΔXseff of $FeSe_{0.3}Te_{0.7}$ film depending on temperature. The inset presents the resistivity temperature dependence.

$FeSe_{0.3}Te_{0.7}$

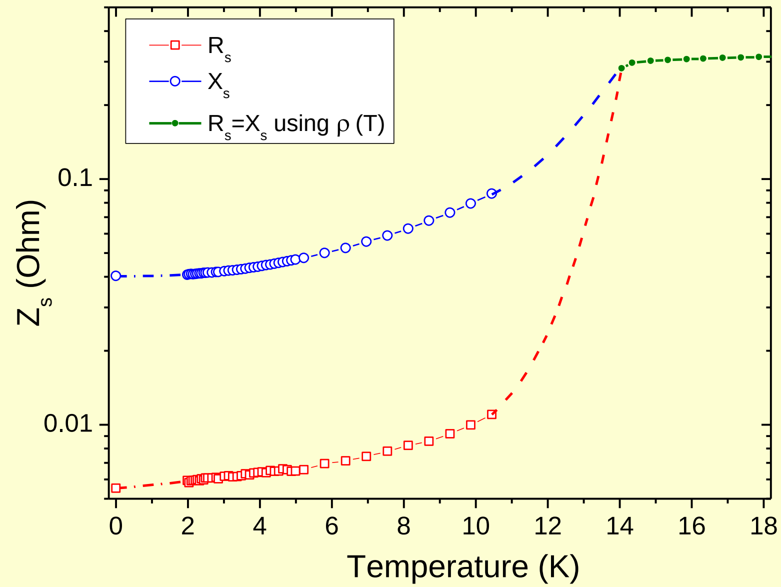


Figure 8. Surface resistance *Rs(T) and surface reactance Xs(T).*

$FeSe_{0.3}Te_{0.7}$

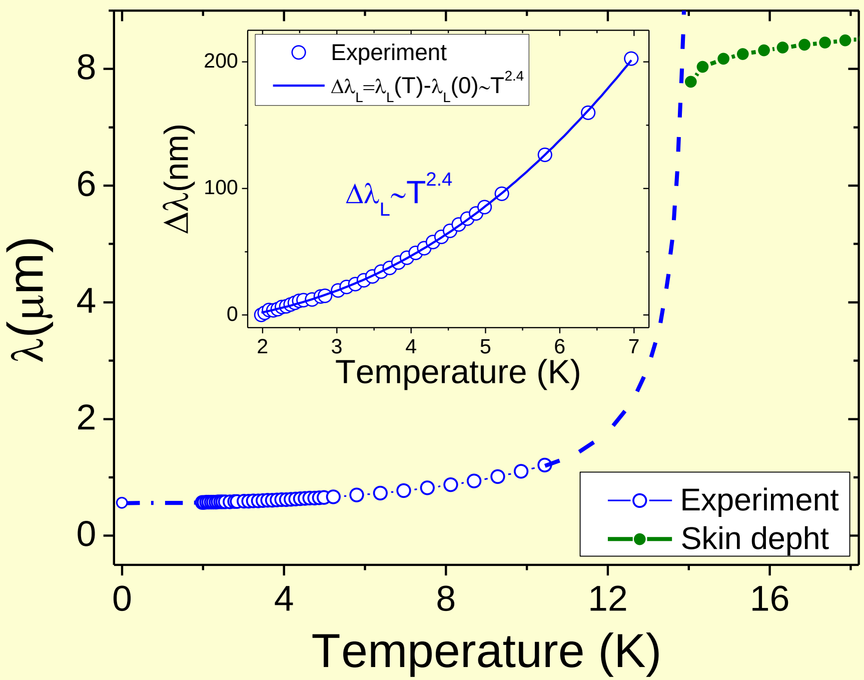


Figure 9. $\lambda_L(T)$ in $FeSe_{0.3}Te_{0.7}$ film. The inset presents LT part of the dependence.

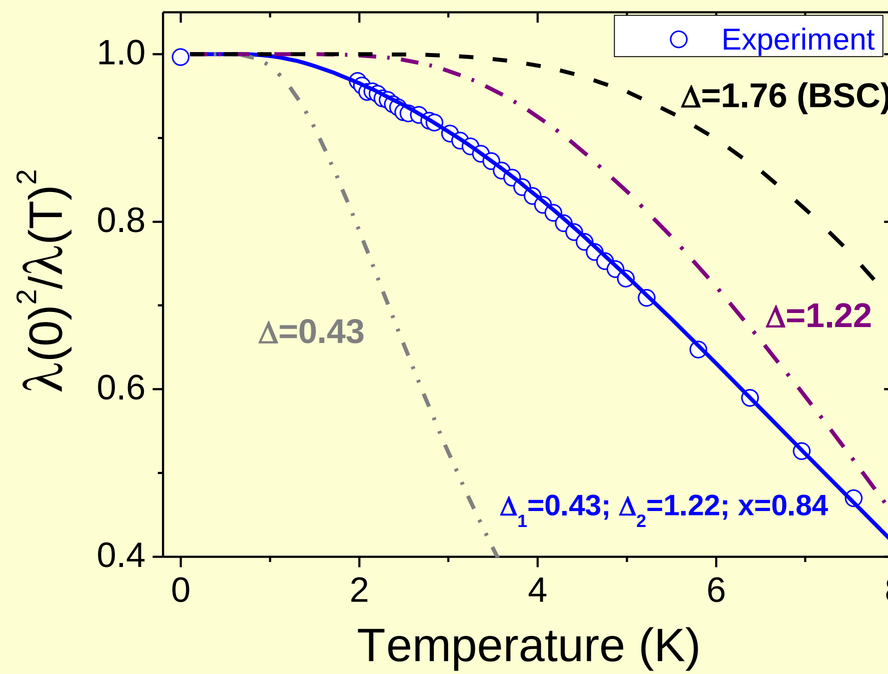


Figure 10. $[\lambda_L(0)\ /\lambda_L(T)]^2$ depending on temperature.

The solid line corresponds to power-law behavior CT^n with $n = 2.4$.

The solid line corresponds to the two-gap model ($\Delta_1 = 0.43\ kT_c$; $\Delta_2 = 1.22\ kT_c$).

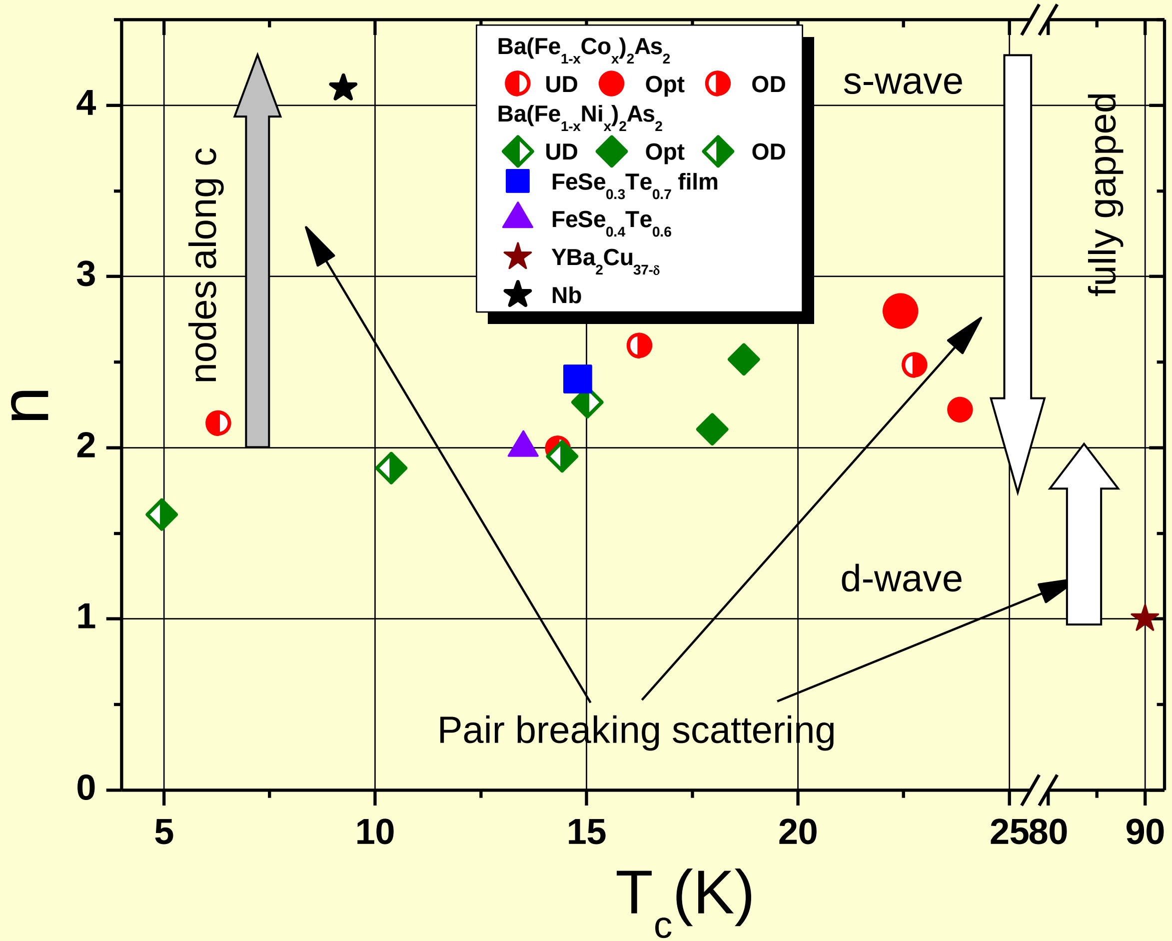
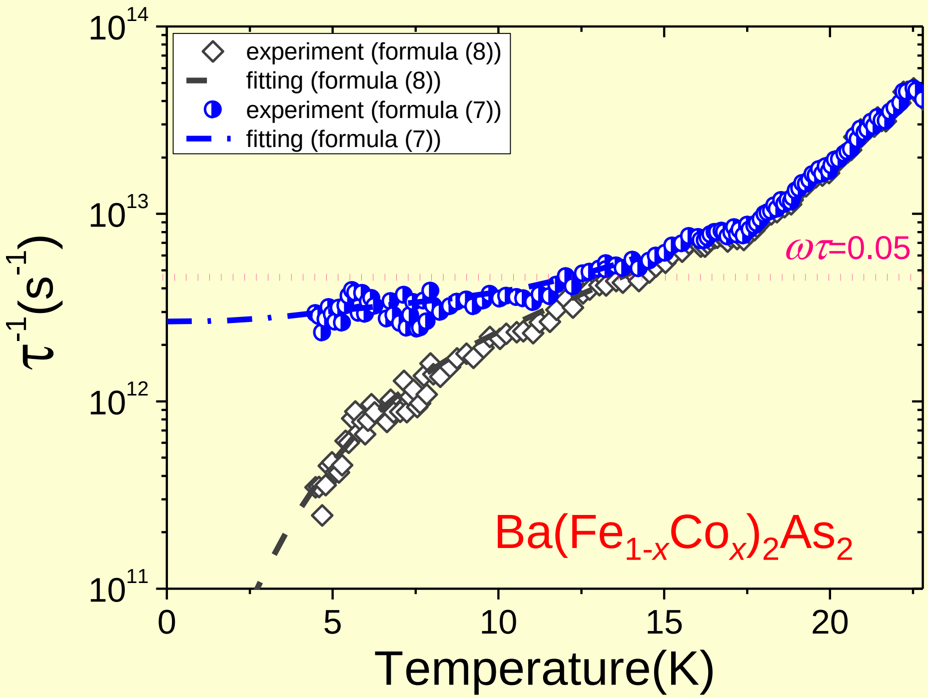


Figure 11. Power-law exponent of the LT variation of in-plane *λab(T)* in several SCs

Figure shows the influence of pair-breaking scattering process approaching from either the s-wave side or d-wave side. A grey arrow shows pair-breaking scattering strength in case of extended s-wave with nodes predominantly along the c-axis.

- Prozorov & Kogan *proposed the model in* Rep. Prog. Phys. 74, 124505 (2011).

4. Quasi-particle scattering



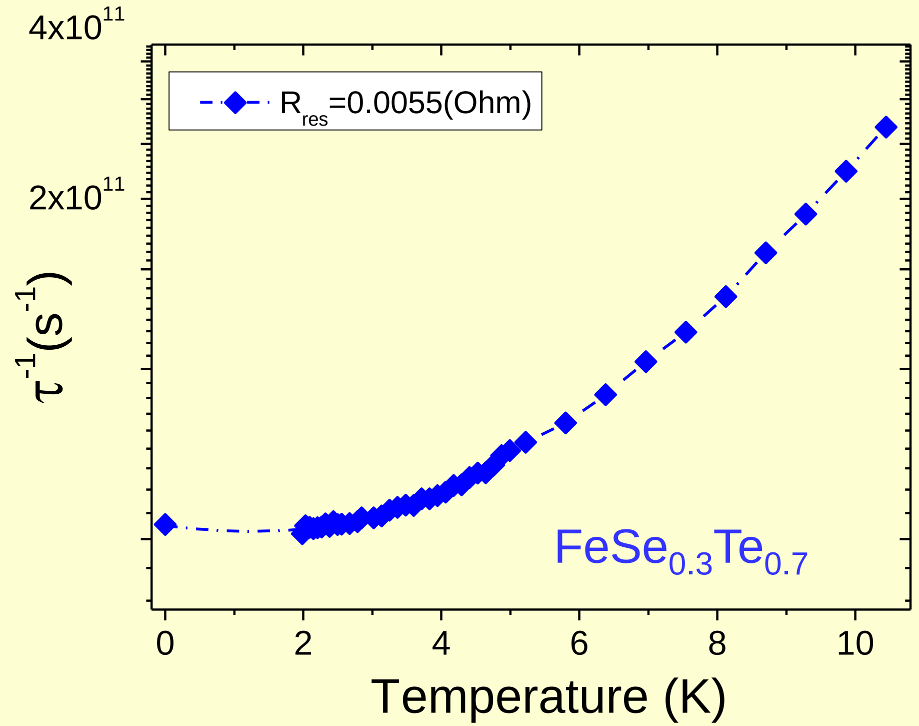


Figure 12. The temperature dependence of the quasiparticle scattering rate τ^{-1} in a single crystal of optimally-doped $Ba(Fe_{1-x}Co_x)_2As_2$ calculated using the generalized expression (7) and the expression (8) valid at $\omega\tau \ll 1$ (The horizontal dotted line shows τ^{-1} for $\omega\tau$=0.05) (a) and in thin epitaxial $FeSe_{0.3}Te_{0.7}$ film (b)

5. Conclusion. What does MW technique allow doing?

- Two MW techniques based on high-Q sapphire resonators were developed for Z_s measurements of unconventional SCs. They allow accurate studying their $\sigma = \sigma_1 - i\sigma_2$ and hence properties of electron systems depending on *T*.

- Power-law dependence in $\Delta\lambda(T) \propto T^n$ with exponents n=2.8 and n=2.4 were found for OD $Ba(Fe_{1-x}Co_x)_2As_2$ and $FeSe_{0.3}Te_{0.7}$ accordingly. Consensus is very good for $Ba(Fe_{1-x}Co_x)_2As_2$.

- The experimental results supports the extended s-pairing symmetry (i.e. s± symmetry) with pair breaking scattering.

- MW technique allows studying the quasiparticle scattering depending on *T*.

- The authors believe that the study should be continued until full consensus on all of the physical properties of all the Fe-SC families.

- There are a number of unsolved problems, such as:
  - the value and original of residual MW surface resistance $R_{res} = R_s(T=0)$
  - the complex conductivity above T_c with the mystery of PG state
  - the QP scattering processes.

Thank you for attention