Microwave properties of Fe(Se,Te) thin films in a magnetic field: pinning and flux flow

Nicola Pompeo¹, Andrea Alimenti¹, Kostiantyn Torokhtii¹, Giulia Sylva²,³, Valeria Braccini², Enrico Silva¹
¹ Dipartimento di Ingegneria, Università Roma Tre, Roma, Italy
² CNR-SPIN, Corso Perrone 24, Genova, Italy;
³ University of Genova, Via Dodecaneso, 33, GENOVA - ITALY
E-mail: nicola.pompeo@uniroma3.it

Abstract. We present here a microwave (16 GHz) investigation of the complex surface impedance in a dc magnetic field (up to 1 T) of Fe(Se,Te) thin (~300 nm) films. We derive the vortex parameters: the flux-flow resistivity yields information on the dynamics of the quasiparticles, the Labusch parameter yields a measure of the steepness of the pinning potential wells, and the depinning frequency assesses the frequency range where the material is suitable for high-frequency applications in a dc magnetic field. We compare the results to the data obtained in YBCO, Nb and Nb₃Sn.

1. Introduction
Iron-Based Superconductors (IBS) are particularly interesting for applications thanks to their relatively high upper critical fields, low anisotropy, good grain connectivity [1, 2]. Their physics is also very intriguing, thanks but not limited to the strict relationship between the superconducting pairing mechanism and the magnetic orderings appearing in their phase diagrams. Among the various iron-superconductors families, the FeSeTe system is subject of intense studies because of many peculiarities. The simple crystal structure and the absence of As make it simple to be grown. The critical current density values achieved ($J_c \sim 1$ MA/cm² in self field at $\sim$4 K [3, 5], the possibility to tune its effective anisotropy and pinning properties through proper substrate choices (CaF$_2$ with respect to SrTiO$_3$ or LaAlO$_4$) [4, 5], make this material promising for d.c. applications. It is therefore interesting to determine how it behaves in high frequency regimes, where thin films are a natural choice for applications. Microwaves are a powerful tool to access fundamental parameters of vortex physics, such as the flux flow resistivity, the Labusch parameter (pinning constant) and the depinning frequency, which are relevant also in view of applications. Hence, we present here a high frequency (16.5 GHz) study of the surface impedance in the mixed state of FeSe$_{0.5}$Te$_{0.5}$ thin films with statically applied magnetic fields up to 1 T, normal to the sample surfaces (i.e. parallel to their c-axis). Through standard high-frequency vortex motion models [6, 7] we extract and discuss the relevant vortex parameters. The paper is structured as follows. In Sec. 2 the samples preparation and characterization are provided. Section 3 presents the experimental setup and the relevant electromagnetic and vortex motion models. In Sec. 4 measurements are presented and analysed. Finally some conclusions are drawn in Sec. 5.
2. Sample preparation and characterization

Fe(Se,Te) thin films were deposited on oriented 001 CaF$_2$ single crystals in an ultra-high vacuum Pulsed Laser Deposition (PLD) system equipped with a Nd:YAG laser at 1024 nm using a FeSe$_{0.5}$Te$_{0.5}$ target prepared by direct synthesis with a two-step method [8]. The deposition was carried out at a residual gas pressure of 10$^{-8}$ mbar while the substrate was kept at 350 °C. The optimized laser parameters to obtain high quality epitaxial thin films were a 3 Hz repetition rate, a 2 J/cm$^2$ laser fluency (2 mm$^2$ spot size) and a 5 cm distance between target and sample [5]. After the deposition, the films were characterized by X-ray diffraction (XRD) with a four-circle diffractometer. The XRD analysis confirms the phase purity and the optimum epitaxial growth of all the films. Moreover, Φ scans confirms that, as already reported [9], the films grow rotated by 45° with respect to the a axis due to the good matching with the half of the diagonal of CaF$_2$ crystalline cell.

For the microwave measurements, presented in the following sections, we focus on a square sample of thickness $d = 300$ nm and side 5 mm.

3. Experimental technique and models

The surface impedance $Z = R + iX$ of the thin films is measured by means of a dielectric-loaded resonator using a surface perturbation technique [10, 11]. The (flat) sample to be measured replaces part of the conducting walls delimiting the resonator volume. Through its surface resistance $R$ and reactance $X$, the sample contributes, respectively, to the resonator losses (determining the resonator unloaded quality factor $Q$) and electromagnetic storage (which determines the resonant frequency $f_0$ of the selected electromagnetic mode).

The resonator used for the measurements consists in a cylindrical OFHC copper cavity, loaded with a coaxial sapphire dielectric puck. In order to accommodate the sample on the resonator base, a thin metal mask with a circular hole has been placed between the sample and the dielectric puck. The resonator is excited on the $TE_{011}$ mode, having resonant frequency $f_0 = 16.5$ GHz, which induces in-plane currents on the sample surface, and it is operated in transmission. The frequency-dependent transmission coefficient $S_{21}$ between the resonator coupling ports is measured through a Vector Network Analyser and fitted against a generalized Fano resonance curve [12] in order to extract the loaded quality factor $Q_l$ and the resonant frequency $f_0$. The resonator is strongly undercoupled, so that $Q_l \simeq Q$. From $Q$ and $f_0$, within the perturbative approach [13], the surface impedance $Z$ is determined as:

$$Z = R + i\Delta X = G_s \left( \frac{1}{Q} - 2i\frac{\Delta f_0}{f_0} \right) - \text{background}$$

where $G_s$ is a computed geometrical factor dependent on the selected resonant mode and on the location and extension of the surface covered by the sample. The expression $\Delta A = A(x) - A(x_{ref})$ refers to the variation of the quantity $A$ with respect to the external parameter $x$, in our case either the temperature $T$ or the static magnetic field $H$. A proper calibration of the resonator is required to determine its “background” contribution [12].

From the measured surface impedance $Z$, the superconductor complex resistivity $\tilde{\rho}$ is derived $\tilde{\rho}/d \simeq Z$ in the so-called thin film approximation [14], which essentially requires that that the film is grown on insulating substrates and that its thickness $d \ll (\lambda, \delta)$, where $\lambda$ and $\delta$ are the London penetration depth and the normal carrier skin depth, respectively.

In figure 1, the measurement of the $Q$ vs the temperature $T$ at zero field is shown. It is apparent the superconducting transition, yielding a critical temperature $T_c$, as estimated by the disappearance of the superconducting signal, 18 ± 0.5 K, consistent with the value determined through d.c. resistance measurements (not reported here). In the normal state, with $G_s = 62$ kΩ, the measured $Q$ yields a normal state resistivity $\rho_n \simeq 3 \cdot 10^{-6}$ Ωm, which is consistent both with
the d.c. values measured in similar samples (not reported here) and with literature, either films of equal or similar composition [15, 16] and single crystals [17].

The superconductor complex resistivity \( \tilde{\rho} \) in the mixed state at high frequency, which is the focus of this paper, is determined by several contributions, which include the superfluid and quasi-particles currents and vortex motion [18]. By focusing on field-induced variations at fixed \( T \) and with negligible pair-breaking effects for fields \( H \ll H_c2 \), \( \Delta \tilde{\rho}(H) \simeq \rho_{cm}(H) \), i.e. the vortex motion resistivity \( \rho_{cm} \) determines the superconductor magnetic response.

In the microwave frequency range, vortices perform very small oscillations around their equilibrium positions (typically pinning centers). Evaluating the balance of forces acting on individual vortices (single-vortex regime) [19], \( \rho_{cm} \) can be obtained and cast, on very general grounds ([7] and references therein), in the following form:

\[
\rho_{cm} = \rho_{cm1} + i\rho_{cm2} = \rho_{ff} \frac{\chi + i\frac{f}{f_c}}{1 + i\frac{f}{f_c}}
\]  

where \( f \) is the measuring frequency, equal to the resonant frequency \( f_0 \) of the resonator, \( \rho_{ff} \) is the flux flow resistivity, inversely proportional to the vortex viscosity \( \eta = \Phi_0 B/\rho_{ff} \), \( \chi \) is the creep factor taking into account thermal effects, and \( f_c \) is a characteristic frequency. For zero creep \( \chi = 0 \), the above expression reverts to the well-known Gittleman and Rosenblum (GR) [6] model, with \( f_c \rightarrow f_p = k_p/(2\pi\eta) \). The quantities \( k_p \) and \( f_p \) are the pinning constant (also called Labusch parameter) and pinning frequency, respectively. The former describes the elastic constant of the recall force which pins vortices to their equilibrium positions, and measures the steepness of the pinning wells. In this respect it conveys complementary information with respect to d.c. measurements of the critical current density \( J_c \), which depends on the height of the pinning wells. The pinning frequency \( f_p \) separates the low-frequency low-dissipation regime \( f \ll f_p \) where the pinning recall force on vortices dominates their oscillations around the pinning centers, from the high-frequency dissipative regime \( f \gg f_p \) where vortex oscillations are so short and fast that pinning effect is negligible and vortices move freely so that \( \rho_{cm} \rightarrow \rho_{ff} \). It is worth mentioning that, within the GR model, the (normalized) pinning frequency can be readily computed through the experimental parameter \( \rho = \Delta X/\Delta R = \rho_{cm2}/\rho_{cm1} = f_p/f \).

Considering now \( \rho_{ff} \), this quantity (and its parent quantity \( \eta \)) accounts for the dissipation due to vortex motion and depends on the quasi-particles scattering time and available energy states in the vortex cores, thus providing an unique window on the fundamental physics of a superconductor. For example, in the classic Bardeen-Stephen model [20] for dirty s-wave superconductors, the dissipation due to vortex motion is attributed to the quasi-particle currents flowing in the vortices “normal” cores, so that \( \rho_{ff} = \alpha \rho_n B/B_{c2} \) with \( \alpha = 1 \), where \( \rho_n \) and \( B_{c2} \) are respectively the normal state resistivity and the upper critical field. The \( \rho_{ff} \) field dependence often departs from the straight linear one. In particular, the slope \( \alpha \) at low fields can be \( <1 \), with specific values obtained through the microscopic theory or a Time-Dependent Ginzburg Landau theory depending on the temperature ranges and on the type of scatterers [21, 22, 23, 24]. On the other hand, superconductors with nodal gaps [25] or fully-gapped with multiple bands [26], like IBS [1], are expected to present \( \alpha > 1 \).

4. Results
We consider field sweeps measurements at fixed temperatures, where the sample is cooled in zero field conditions, thermalized at the desired temperature and then subjected to a static magnetic field applied normally to the sample surface.

An example is reported in figure 2, where the field induced variations of the surface resistance \( \Delta R_s(H) \) and of the surface reactance \( \Delta X_s(H) \) are reported at the selected temperature \( T = 12 \) K \( (t = T/T_c = 0.67) \) versus \( B \simeq \mu_0 H \) in the London limit. The surface resistance increases with
the field, as expected since the fluxons, whose motion determines the dissipation, increase in number \(\propto B\).

It can be noted that \(\Delta X > \Delta R\) in the whole field range. Hence, in the assumption of zero creep, the obtained \(r = f_p/f \sim 1.3 > 1\), almost field-independent, yields a quite high pinning frequency \(f_p = 21.5\) GHz, near that of FeSe\(_{0.4}\)Te\(_{0.6}\) single crystal measurements \((f_p = 16\) GHz at \(t=0.71, T_c = 14\) K) [17], and larger than other IBS (6 GHz in LaFeAsO\(_{0.9}\)Fe\(_{0.1}\) [27] and 3 GHz in LiFeAs single crystals [28]). Further comparisons can be made considering other superconductor materials: polycrystal Nb\(_3\)Sn exhibited \(f_p = 6.3\) GHz at 12 K and low fields \((\sim 2\) T) [29]; Nb thin films yielded 5.0 GHz at \(t=0.8\) \((T_c = 6.0\) K) and 0.6 T [30]. On the other hand, the present FeSeTe \(f_p\) is definitely lower than the values obtained in the more technologically mature YBa\(_2\)Cu\(_3\)O\(_{7-x}\) (YBCO). Considering various YBCO PLD thin films, both pure and BaZrO\(_3\)-added, \(f_p\) has been observed to range between 35 and 60 GHz, as measured at \(t \sim 0.68\) and \(B = 0.5\) T [31], and as high as 65 GHz in Ba\(_2\)Y(Nb/Ta)O\(_6\)-added YBCO, as measured at \(t \sim 0.72\) and \(B = 0.5\) T [32, 33]. Finally, considering instead the same absolute \(T = 12\) K, measurements performed on a PLD BaZrO\(_3\)-added 100 nm YBCO thin film yielded \(f_p = 31\) GHz at \(\sim 2\) T [34].

In order to better characterize this relatively high pinning effect in the present FeSeTe thin film, we extract the flux flow resistivity \(\rho_{ff}\) and the pinning constant \(k_p\), within the zero-creep GR model.

The extracted pinning constant is reported in figure 3. The negligible positive slope allows to consider it essentially constant vs the field: the absence of a decreasing trend indicates that there is an individual pinning regime where vortices are pinned without significant interactions among the vortex lattice.

The absolute value, \(k_p(0.5\) T\) = 860 N/m\(^2\) is rather low if compared with YBCO values \((10^4-10^5\) N/m\(^2\) [31, 32, 33, 34]) at the same field and reduced temperatures, and it is potentially lower also than the one that could be expected in from the above mentioned data on the FeSe\(_{0.4}\)Te\(_{0.6}\) single crystal [17] (a value \(k_p = 14\) kN/m\(^2\) at 2 K and 2 T can be computed). In order to further analyse the meaning of this \(k_p\) value, we can first compare it with the maximum, theoretical value \(k_{p,full}\) which could arise if fluxons were pinned along their full length. Equating the pinning elastic energy with the condensation energy lost in the vortex core, the following expression can be obtained[19, 35]: \(k_{p,full} = c_kH_c\Delta\Phi_0/(4\pi\lambda^2(T))\), with \(c_k\) a constant of the

---

**Figure 1.** Quality factor \(Q\) vs \(T\) at zero field.

**Figure 2.** Field-induced surface impedance variation, real (full dots) and imaginary (open symbols) parts, at 12 K.
order of unity. Taking $B_{c2}(t = 0.67) \approx 37$ T as measured on similar samples [9], literature [17] values for the London penetration depth at zero temperature $\lambda(0) \sim 550$ nm, and using a rough extrapolation for $\lambda(t) = \lambda(0)/\sqrt{1-t^2}$ through the GL expression, $k_{p,\text{full}} \sim 9000$ N/m$^2$. The latter is one order of magnitude larger than the measured $k_p$ so that, clearly, the uncertainties connected to this crude evaluation do not alter the result. Since the actual $k_p$ is much smaller than the computed $k_{p,\text{full}}$, this suggests that vortices are pinned only for a fraction of their length, presumably by short, not extended defects. This is consistent with the small anisotropy in the critical current $J_c$ observed on similar FeSeTe samples grown on CaF$_2$ substrates [5], where SEM analyses have shown that the substrate promotes the appearance of small 3D isotropic defects (as opposed to SrTiO$_3$ substrate which determined elongated defects). A further insight can be obtained relating the high frequency, short range evaluation of the pinning force, through $k_p$ with the different, d.c. regime, where the relevant quantity is the critical current density $J_c$. Equating the maximum pinning force per unit length $k_p\xi$ with the maximum Lorentz force per unit length $J_c\Phi_0$, an equivalent critical current density at microwaves [36] can be obtained $J_{c,mw} = k_p\xi/\Phi_0$, with $\xi = \sqrt{\Phi_0/(2\pi B_{c2})}$. This expression shows that higher $k_p$ should be expected with higher $J_c$, one of the reasons why $J_c$-optimized YBCO exhibit $k_p$ values much larger that the present FeSeTe. The computed value $J_{c,mw} = 130$ kA/cm$^2$ and the $J_{c,dc} \sim 300 - 400$ kA/cm$^2$ value, measured on similar samples in the same $T - B$ range [5], are of the same order of magnitude. Phenomenologically, $J_{c,mw} < J_{c,dc}$ indicates that the pinning potential wells, for a given height ($\propto J_{c,dc}$), have a small steepness ($\propto J_{c,mw}$) in the bottom.

Finally, a last consideration can be done considering the flux flow resistivity. The extracted $\rho_{ff}$ at 12 K, normalized to the normal state resistivity, is reported against the normalized magnetic field in figure 4. For comparison purposes, the BS model behaviour is also sketched as a dashed line. It can be seen that the measured $\rho_{ff}$ is well above it, corresponding to a slope $\alpha \sim 4.0 > 1$. This behaviour is consistent with the multi gap nature of FeSeTe [37, 38], analogous to other IBS [28, 39] and also to multi gap superconductors like MgB$_2$ [40, 41].

It is worth mentioning that, although FeSeTe have been observed to have an upper critical field limited by an important spin-paramagnetic effect, so that the experimental $B_{c2}$ is lower than theoretical orbital-only pair-breaking upper critical field to be used in the BS computation [17, 20, 42, 43], the correction upwards on the determined slope is within $\sim 20\%$, which therefore does not alter at all the conclusions.
Nevertheless, this result $\alpha > 1$ is at odds with result on FeSeTe single crystal as reported in Ref. [17], where $\alpha(t = 0.13) = 0.78 < 1$ was observed. The authors, commenting on that anomalous behaviour, suggested that it could be due to the combination of a small excess of Fe, acting as magnetic impurity, with the disorder in the Se/Te atoms, acting as nonmagnetic impurities.

Considering also the pinning frequency result, it is possible now to recognize that the high value obtained for $f_p$ in the present sample is mainly due to small viscosity $\eta$ (inversely proportional to the high $\rho_{ff}$ observed), instead of a large $k_p$. This detail is relevant for the applications, since an high $\rho_{ff}$ implies large dissipation in magnetic fields even if $f_p$ is favorably high: as an example, referring to the PLD BaZrO$_3$-added 100 nm YBCO thin film above mentioned, it yielded a surface resistance $R(12 \text{ K}, 2 \text{ T})$=0.007 $\Omega$ [34] much smaller than the measured $R(12 \text{ K}, 0.75 \text{ T})$=~ 0.5 $\Omega$ of the present FeSeTe sample, despite the similar pinning frequencies. In the single crystal of Ref. [17], the relative situation for $k_p$ and $\eta$ was instead the opposite. This is not necessarily surprising, given the different geometries (thin film vs single crystal), the different compositions (nominal FeSe$_{0.5}$Te$_{0.5}$ vs FeSe$_{0.4}$Te$_{0.6}$), presumably different excess of Fe-magnetic impurities. Considering the already recognized disorder of FeSeTe material, due to the Se-Te substitution, the structural transition of the parent compound FeSe and the phase separation occurring at various $x$ compositions of FeSe$_{1-x}$Te$_x$ [44], many degrees of freedom are available to obtain different pinning landscapes. Moreover, considering the impact that impurities and disorder have on the quasi-particle scattering time, the same properties influencing pinning are capable of modifying $\rho_{ff}$ and $\eta$. This is even more evident in IBS where quantized Caroli-De Gennes-Matricon [45] discrete energy levels in the vortex core have been observed (FeSe$_{0.55}$Te$_{0.45}$ single crystal) [46], even with different energy level distributions depending on the localization of specific vortex cores in the same sample [46, 47].

5. Conclusions
We have presented a high frequency (16.5 GHz) study of the mixed state response of FeSe$_{0.5}$Te$_{0.5}$ thin film grown on CaF$_2$ substrate, performed through surface impedance measurements based on a dielectric-resonator based resonant technique. We have observed relatively high values for the pinning constant $f_p = 21.5$ GHz, in line with similar results on single crystal and superior to other IBS. A comparison with traditional superconductors Nb and Nb$_3$Sn in terms of $f_p$ is favorable for FeSe$_{0.5}$Te$_{0.5}$, but its high dissipation on the vortex cores, testified by $\rho_{ff}$ values in excess of the Bardeen-Stephen limit, requires further understanding in view of high-frequency applications in moderate fields. The common properties of IBS (high $B_{c2}$, small anisotropy, good grain connectivity) together to the specific traits of FeSeTe, make these materials very attractive. In particular, the sensitivity of FeSeTe systems on disorder (tunable through Se-Te balance, by specific substrates for the growth, by controlled excess-Fe), both in terms of pinning forces and dissipation in the vortex cores, potentially allows for many design degrees of freedom to be exploited for their optimization. As a further route, the addition of artificial pinning centers as done in cuprate superconductors could be also considered. All these contributions can be tailored also for high frequency applications.

Acknowledgments
Work partially supported by MIUR-PRIN project “HiBiSCUS” - grant no. 201785KWLE.

References
[1] Hosono H and Kuroki K 2015 Phys. C 514 399-422
[2] Hosono H, Yamamoto A, Hiramatsu H and Ma Y 2017 Mater. Today 21 278-302
[3] Mele P, Matsumoto K, Haruyama Y, Mukaida M, Yoshida Y, Ichino Y, Kiss T and Ichinose A 2010 Supercond. Sci. Technol. 23 052001
[4] Tsukada I et al 2011 Appl. Phys. Express 4 053101
[5] Braccini V et al 2013 Appl. Phys. Lett. 103 172601
[6] Gittleman J I and Rosenblum B 1966 Phys. Rev. Lett. 16 734-736
[7] Pompeo N and Silva E 2008 Phys. Rev. B 78 094503
[8] Palenzona A et al 2012 Supercond. Sci. Technol. 25 115018
[9] Bellingeri et al 2014 Supercond. Sci. Technol. 27 044007
[10] Klein O, Donovan S, Dressel M and Grünér G 1993 J. Infrared Millim. Terahertz Waves 14 2423-2456
[11] Donovan S, Klein O, Dressel M, Holzer K and Grünér G 1993 J. Infrared Millim. Terahertz Waves 14 2445-2487
[12] Pompeo N, Torokhtii K and Silva E, Meas. Sci. Rev. 14, 164-170 (2014)
[13] Staelin D H, Morgenthaler A W and Kong J A 1994 Electromagnetic waves (Englewood Cliffs, NJ: Prentice-Hall Inc.)
[14] Pompeo N, Torokhtii K and Silva E 2017 IEEE Int. Instrumentation and Measurement Technology Conf I2MTC (Torino) 1-5, doi: 10.1109/I2MTC.2017.7969902
[15] Zhang J et al 2014 Sci. Rep., 4 7273
[16] Imai Y et al 2015. PNAS, Proc. of the National Academy of Sciences, 112 937-1940
[17] Okada T et al 2015 Phys. Rev. B 91 035410
[18] Colley M W and Clem J R 1991 Phys. Rev. Lett. 67 386-389
[19] Golosovsky M, Tsindlekht M and Davidov D 1996 Supercond. Sci. Technol 9 1-15
[20] Bardeen J and Stephen M J 1965 Phys. Rev. 140 1197-1207
[21] Gor’kov L P and Kopnin N B 1975 Sov. Phys.-Usp.
[22] Larkin A I and Ovchinnikov Yu N 1986 Vortex Motion Superconductors
[23] Kopnin N B 2001 Theory of Nonequilibrium Superconductivity (Oxford: Clarendon Press)
[24] Vargunin A and Silaev M A 2017 Phys. Rev. B
[25] Kopnin N B and Volovik G E 1997 Phys. Rev. Lett. 79 1377-1380
[26] Silaev M A and Vargunin A 2016 Phys. Rev. B 94 224506
[27] Narduzzo A et al 2008 Phys. Rev. B 78 012507
[28] Okada T, Takahashi H, Imai Y, Kitagawa K, Matsubayashi K, Uwatoko Y and Maeda A 2012 Phys. Rev. B 86 064516
[29] Alimenti A, Pompeo N, Torokhtii K, Spina T, Flikiger R, Muzzi L and Silva E 2019 IEEE Trans Appl Supercond 29 1-4
[30] Silva E, Pompeo N and Sarti S 2011 Supercond. Sci. Technol. 24 024018
[31] Pompeo N, Rogai R, Augieri A, Galluzzi V, Celentano G and Silva E 2009 J. Appl. Phys. 105 013927
[32] Frolova A et al 2018 IEEE Trans. Appl. Supercond. 28 7500805
[33] Torokhtii K, Alimenti A, Rizzo F, Augieri A, Celentano G, Frolova A, Silva E, Pompeo N “High frequency vortex dynamics in YBa2Cu3O7-x with Ba2YTaO6 -Ba2YNbO6 nano defects”, paper n. 3-MP-F5-S09, submitted to European Conf. on Applied Superconductivity EUCAS 2019 (Glasgow)
[34] Silva E et al 2017"Pinning, dissipation and anisotropy in nanostructured YBa2Cu3O7-x from microwave measurements”, poster 3MP1-04 presented at European Conf. on Applied Superconductivity EUCAS 2017 (Geneva)
[35] Pompeo N, Torokhtii K, Cirillo C, Samokhvalov A V, Ilyina E A, Attanasio C, Buadin A I and Silva E 2014 Phys. Rev. B 90 064510
[36] Pompeo N, Augieri A, Torokhtii K, Galluzzi V, Celentano G and Silva E 2013 Appl. Phys. Lett. 103 022603
[37] Hanaguri T, Niitaka S, Kuroki K and Takagi H 2010 Science 328 474-476
[38] Okada T, Takahashi H, Imai Y, Kitagawa K, Matsubayashi K, Uwatoko Y and Maeda A 2012 Phys. Rev. B 86 144525
[39] Shibata A, Matsumoto M, Iwasa K, Matsuda Y, Lee S and Tajima S 2003 Phys. Rev. B 68 060501
[40] Alimenti A, Torokhtii K, Grigoroscuta M, Badica P, Crisan A, Silva E, Pompeo N “Microwave investigation of pinning in Te- and cubic-BN-added MgB2”, paper n. 2-MP-FP3-S12, submitted to European Conf. on Applied Superconductivity EUCAS 2019 (Glasgow)
[41] Khim S, Kim J W, Choi E S, Bang Y, Nohara M, Takagi H and Kim K H 2010 Phys. Rev. B 81 184511
[42] Lei H, Hu R, Choi E S, Warren J B and Petrovic C 2010 Phys. Rev. B 81 094518
[43] Imai Y, Sawada Y, Nabeshima F, Asami D, Kawai M and Maeda A 2017 Sci. Rep. 7 46653
[44] Caroli C, De Gennes P G and Matricon J 1964 Phys. Lett. 9 307-309
[45] Chen M, Chen X, Yang H, Du Z, Zhu X, Wang E and Wen H 2018 Nat. Commun. 9 1-7
[46] Berthod C 2018 Phys. Rev. B 98 144519