VORTEX MATTER, DYNAMICS AND PINNING IN SUPERCONDUCTING MATERIALS

by **Dr. Ioan Adrian Crisan**

UNIVERSITY OF BIRMINGHAM

Body of work submitted to The University of Birmingham

for the Higher Doctorate degree of

DOCTOR OF SCIENCE

Synopsis

The enclosed body of work represents a compilation of published papers covering work carried out in the Universities of Birmingham, Bath and Southampton, UK, in the Second University of Rome “Tor Vergata”, Italy, in the Nanoelectronics Research Institute (former Electrotechnical Laboratory) of AIST Tsukuba, Japan, and in the National Institute of Materials Physics (former Institute of Physics and Technology of Materials), Bucharest, Romania, during my research career over more than twenty years. The thesis comprises mainly research work on science and technology of high temperature superconducting cuprates of various compositions (Y-based, Bi-based, Tl-based, Hg-based, (Cu,C)-based) and morphologies (polycrystalline, single crystals, thin films, tapes, artificial superconducting superlattices). The major theme common to most of the research done on the above-mentioned materials is the study of vortex matter, dynamics, and pinning, which determine a large number of superconducting properties for various applications.

The submitted work presents the results of experimental and fundamental studies of superconducting materials in six main areas. These comprise: (i) synthesis and characterization (current-voltage characteristics, dissipation mechanisms, interaction between inter-and intra-grain vortices) of Y- and Bi-based superconducting ceramics; (ii) experimental and theoretical studies of current-induced unbinding of thermally-created vortex-antivortex pairs; (iii) fabrication and characterization of artificial superconducting superlattices; (iv) fabrication and characterization of anomalous superconductors, two- and multi-component superconductors, and exotic vortex matter; (v) study of vortex matter and dynamics by Scanning Hall Probe Microscopy; and (vi) science and technology of vortex pinning, including through self-assembling nanotechnology of pinning centres. There are a small number of publications that do not fall in the above-mentioned areas, but they are also in the larger field of science and technology of superconducting materials. The papers are presented essentially chronologically, with no attempt to group them into separate research areas, since the common philosophy and approach to the investigation of various superconducting materials is to determine how vortex matter, dynamics and pinning influence their physical properties.

The first group of papers [2-4, 6-9, 11-12, 15] concerns the fabrication and studies of superconducting properties from transport measurements of Y- and Bi-based polycrystalline superconductors, in the first decade after the discovery of high critical temperature superconductivity, when many groups around the world were deeply involved in the comprehensive research of these materials and corresponds to the subject of my PhD studies (work done in Bucharest). In their ceramic form, in Y- and Bi-based cuprates the factor that is limiting the transport current capability is the thermal activation of inter-grain Josephson vortices [3,4], the peak-effect in the magnetic field dependence of the transport critical current density is due to the attractive interaction between the intra-grain Abrikosov vortices and the inter-grain Josephson vortices [9], while in moderate magnetic fields the current voltage characteristics are well described by a modified Kim-Anderson model [6].

The second group of papers [10, 13, 16-17, 19] concerns the investigation of dissipation in zero applied magnetic field in various superconducting materials and various morphologies (single-crystals, epitaxial thin films, ceramics with and without preferentially-oriented grains, mono- and multi-filamentary tapes). The work on the subject started in Rome in 1994, and continued in Bucharest and Southampton for other 3 years. Even in zero applied magnetic field, the critical current density was found to be much smaller than the de-pairing critical current. The reason for this fact is that, due to higher thermal energy available around liquid nitrogen temperature, vortex-antivortex pairs are spontaneously created, and a transport current in the system leads to dissipation due to the Lorentz force. From I-V characteristics of Bi:2212 films, we showed that the power law valid for 2D systems does not correctly described the data, and interlayer coupling must be taken into account. We observed a cross-over from 2D to 3D behaviour as the current is reduced. Furthermore, by annealing treatments in redox atmospheres, we changed the interlayer coupling, resulting in an increase of the Jc and a decrease of anisotropy factor with increasing O_2 content in the film. We quantitatively evaluated these effects in terms of current-induced unbinding of the thermally-created vortex-antivortex pairs in a quasi-2D approach. However, at T close to Tc and in the low-voltage region, we observed an additional dissipation, which we explained in terms of fluctuations of the phase of the order parameter [**10**]. We also found that vortex fluctuations are limited also by size effects and by additional pinning. As a consequence of these findings, I was invited to write a chapter on this subject in a book for an international book series published by Nova Science Publishers [24].

The third area of work involves the fabrication and characterization of $(BaCuO_2)_m/(CaCuO_2)_n$ artificial superconducting superlattices grown by layer-by-layer PLD [20-23], the work being done in Rome (1998-1999) under a contract with the National Institute of Physics of Matter, Italy. The thickness of the Charge Reservoir Layer, and the number of superconducting CuO_2 planes could be adjusted at will, and allowed the growth of artificial superconductors that can not be obtained in normal conditions, hence allowed us to play with various superconducting parameters for fundamental research. From various transport measurements, I have clarified for the first time the peculiarities of the vortex dynamics, melting transitions, anisotropy and critical current densities in these artificial structures [**21**], and have demonstrated that the unusual properties of these artificial superlattices (high value of resistivity at room temperature, negative curvature and pronounced rounding well above the transition of R(T) experimental curves, broadening of the transition and strong enhancement of fluctuations contribution to conductivity) can be explained if the high degree of structural disorder is taking into account [**22**]. Furthermore we have shown that normal state resistivity behaviour, enhanced thermodynamic fluctuations, decrease of T_c can be explained by a single numerical value of the localization parameter $\varepsilon_F\tau \cong 3\hbar$.

The fourth area of work involves the fabrication by high-pressure synthesis and characterization of anomalous, exotic superconductors in the (Cu.C)-, Tl-, Hg-, and F-doped cuprate families [26, 35-37, 56-58, 71, 73-78, 80-87, 92-93, 98]. The experimental work was done in Tsukuba (2000-2002, and 2006-2007), while some of the results were analyzed (and papers submitted) in Bucharest, Bath and Birmingham. I have imagined and developed a new, straight-forward method for determining the vortex melting lines by using the third-harmonic susceptibility response [**58**]. Since most of these superconductors are two-component (two-gap), they have a number of quite exotic properties. For example, due to the very small inter-band coupling, they may have an anomalous vortex melting line [**71**], or they may have superconducting CuO_2 outer planes and antiferromgnetic CuO_2 inner planes without the destruction of superconductivity along the c-axis [**73**]. I have discovered two new phases of vortex matter: magnetically-coupled pancake-vortex molecules in super-multi-layered Hg-based cuprates [**80**] and non-axis-symmetric (non-Abrikosov) vortices composed of two fractional flux quanta glued by a inter-band phase difference soliton [**74**]. For the last case, theoretical models and complex phase diagrams were proposed [75, 78, 98, 113]. After the discovery of the new pnictides and chalcogenides superconductors, the interest in two- and multi-component superconductors has increased, so we continued our theoretical analysis [105,107,117] of such materials, based on our previous work on *i*-solitons; most important results being on topological structures of solitons and two-band superconductors, and chiral domains in multi-band superconductors.

The fifth group of papers [59-63, 67-70, 79, 116] concerns the study of vortex matter and dynamics by Scanning Hall Probe Microscopy, the experimental work being done in Bath (2002-2004), while some of the later analysis of results and papers writing being done in Birmingham. We have observed and explained a local hysteresis inversion near the edge of the film [69-60], we have investigated the flux structures in mesoscopic discs [**68**], interacting crossing vortex lattices in single crystals in the presence of quenched disorder [61] and in thin films [**69**], and flux lenses effects [62]. We have also observed and modelled flux channelling and streaming in superconducting films with regular array of micron-sized antidots (holes) [**67**] and demonstrated the manipulation of pancake vortices by a rotating Josephson vortex lattice [79]. In $Bi_2Sr_2CaCu_2O_{8+\delta}$ thin films in very low perpendicular magnetic fields SHPM showed vortices that are intermittently trapped on strong pinning centres. This state shares many of the signatures of the re-entrant vortex liquid phase that has been theoretically predicted in these highly anisotropic materials at very low vortex densities. This is the first direct experimental evidence for the existence of a dynamic liquid-like vortex state in this highly anisotropic material at very low magnetic induction [**116**].

The final research area concerns the science and technology of vortex (flux) pinning. In applied magnetic fields, superconducting materials are subject to additional dissipation due to Lorentz forces, hence their critical current density decreases strongly with increasing magnetic field. To limit this decrease (*i.e.*, to increase critical current in magnetic fields) artificial defects (pinning centres) are needed. These strong artificial pinning centres were introduced (and their influence studied), by doping/substitutions with $BaZrO_3$ [29-31, 38], Zn [39], LiF [54-55] or by heavy-ion or neutron irradiation [43-47], the work being done in Bucharest and Tsukuba (2000-2002). The most significant result in this research area is the invention of self-assembled nanotechnology of pinning centres in superconducting films and devices, which led to a new field in the science and technology of superconducting materials, and to winning of a Marie Curie Excellence Grant with University of Birmingham as host institution. This was the first cost-effective method for introducing extended, correlated artificial pinning centres in films, which led to impressive increase of critical current and other superconducting properties in magnetic fields. The principle of the idea is that by growing an incomplete layer of nano-islands prior to the films deposition, correlated, extended defects that act as very efficient pinning centres form on top of nano-islans. Several variations of the patented method are now used. The work started in Japan in 2001 on Tl-based films [**32-33**, 52-53] and continued in Birmingham (2007 - till now) on YBCO films using various materials as nanodots, and several variations of the initial approach [72, 88-90, 94-97, 99-104, 106, 108-112, 114,115]. Due to the catalytic effect, noble-metal nano-dots in substrate decoration and quasi-multilayers approaches allowed the growth of thick YBCO films (4-6 μm) with a less pronounced decrease of J_c with thickness as compared with pure YBCO films, allowing critical currents as high as 800-900 A/cm-w in self field and 77K [**95**, 97, 104], very close to the best results in the world (USA, Japan) obtained after many years of research, in large, very well funded laboratories or companies. The improvement in applied fields is even larger. Since for cost-effective, energy-efficient electro-technical devices made from coated conductor tapes, the parameter of interest is I_c (superconducting film thickness is negligible in comparison with the substrate thickness), this will have a big impact for the future applications of superconductors. In addition to alleviating the thickness problem, noble metals nanodots promote a closely-packed columnar growth of YBCO, with column boundaries acting as extended, 2-dimensional pinning centres [94, **106**]. The columns diameter (and, consequently, the density of the pinning centres) is well correlated with the dimensions and surface density of the noble metal nanodots. The best results occurred from combining Ag nanodots in substrate decoration and quasi-multilayers with nanocrystalline targets containing 2-4% wt. $BaZrO_3$ (BZO) [**109**, **114**], and showed that Ag helped maintaining a very high T_c (in YBCO/BZO nanocomposite T_c is depressed by few degrees) and promoted the growth of YBCO nanocolumns (nanothreads) entangled with BZO nanorods. The resulting thick nanocomposite films have large critical current both in self field and in applied fields (European record, to our best knowledge) and have a very small anisotropy of critical current for a broad range of applied fields, which is very important in practical applications. As for the theoretical contributions to the study of artificial pinning centres, we have shown [**90**] that the current dependence of the pinning potential in superconducting nano-composites are not described by the Anderson-Kim or collective pinning models, but instead it is described by the logarithmic law as proposed by Zeldov.

The published work comprises 117 papers, the full list being presented before copies of individual papers.

The most important papers, which made the largest impact and contribution to the development of the knowledge and technology in the field, are marked by bold fonts.

Statement indicating the nature and contribution in papers involving joint authorship.

1. I am single author of papers 5-7, 9 and 24
2. As first (principal) author of papers 4, 8, 12-13, 15-16, 19, 21, 23, 26, 28, 32-33, 39, 43-44, 52, 57-60, 67-69, 71-74, 79-82, 88, 90-91, 96, 100, 103, 113, 116, I had the ideas, performed all or part of the measurements and data analysis, wrote the largest parts of the papers, submitted (and revised when needed) for publications. I contributed less to sample preparations.

3. As Group Leader (in Bucharest) or Marie Curie Team Leader (in Birmingham), papers 29-31, 34, 38, 54, 65, 89, 94-95, 97, 101-102, 104, 106, 108-112,114, I coordinated the research, performed in some cases measurements, performed data analysis, wrote or supervised/corrected the final version of the paper.
4. As member of research groups I had contributions to measurements, usually all the data analysis, and I contributed to paper writing (in Japan, I usually wrote/corrected the final version of the papers): 1-3, 10-11, 14, 17-18, 20, 22, 25, 27, 35-37, 40-42, 45-51, 53, 55-56, 61-64, 66, 70, 75-78, 83-87, 92-93, 98-99, 105, 107, 115, 117.

LIST OF PUBLICATIONS

D. Sc.

1. TEA-CO_2 laser deposited $YBa_2Cu_3O_7$ superconducting thin films. V. Sandu, A. Crisan, D. Grigorescu, L. Miu, I. Chis, G. Aldica, E. Cruceanu, C. Grigoriu, D. Dragulinescu, *J. Mater. Sci. Lett*. 8, 509-510 (1989).
2. On the Limiting Factors of the Critical Current Density in High-Tc Superconducting Ceramics. L. Miu, A. Crisan, S. Popa, V. Sandu, L. Nistor**,** *J. Supercond*. 4**,** 391-394 (1990).
3. Dissipation in Current-Carying High-Tc Superconducting Ceramics in Applied Magnetic Field. L. Miu, S. Popa, A. Crisan, G. Aldica, J. Jaklovszky, *J. Supercond*. 6, 279-284 (1993).
4. Critical Current Density and Thermally-Activated Flux Motion in High-Temperature Superconducting Ceramics. A. Crisan and L. Miu, *Romanian Reports in Physics*, 45, 503-514 (1993).
5. Synthesis of Tl-Ba-Ca-Cu-O High Temperature Superconductors From Ba-Ca-Cu-O Precursors. I.A. Crisan, *Romanian Journal of Physics*, 38, 155-157 (1993).
6. On a Modified Kim-Anderson Model of the Current-Voltage Characteristics of High Temperature Superconducting Ceramics. A. Crisan, *J. Supercond*. 7, 687-691 (1994).
7. Dimensionality-Related Collective Pinning Behavior of Vortices in High Temperature Superconducting Ceramics. Adrian Crisan, *Romanian Journal of Physics*, 38, 155-157 (1995).
8. The Influence of the Preparation Conditions on the Superconducting Properties of Laser Deposited Epitaxial $YBa_2Cu_3O_7$ Thin Films. Adrian Crisan, Giovanni Petrocelli and Antonello Tebano, *Romanian Journal of Physics*, 38, 1053-1059 (1995).
9. Current-Voltage Characteristics of High-Temperature Superconducting Ceramics with "Peak-Effect" in the Magnetic Field Dependence of the Transport Critical-Current Density. A. Crisan, *J. Supercond*. 8, 315-320 (1995).
10. **Two-Dimensional Vortex and Phase Fluctuations from Current-Voltage Characteristics of $Bi_2Sr_2CaCu_2O_{8+x}$ Films with Various Oxygen Content. G. Balestrino, A. Crisan, D. V. Livanov, E. Milani, M. Montuori, A. A. Varlamov, *Phys. Rev*. B 51, 9100-9107 (1995).**
11. A New Approach for the Growth of High-Tc Superconductors. J. Jaklovszky, G. Aldica, C. Rusu and A. Crisan, *Appl. Supercond*. 4, 191-194 (1996).
12. Temperature-Dependent Collective Pinning Exponent in $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ Tapes and Bulk samples with Preferential Crystallite Orientation. A. Crisan, S. Popa, G. Aldica and J. Jaklovszky, *J. Supercond*. 9, 295-299 (1996).
13. On the Dissipation Process in $Bi_2Sr_2Ca_2Cu_3O_{10+x}$ Tapes and Bulk Samples with Preferential Grain Orientation in Zero External Magnetic Field. A. Crisan, L. Miu, S. Popa and G. Aldica, *J. Supercond*. 9, 541-545 (1996).

14. AC Magnetic Susceptibility of $Bi_2Sr_2CaCu_2O_8$ Single Crystals. S. Mandache, A. Crisan, G. Aldica and S. Popa, *J. Supercond*. 10, 211-214 (1997).

15. Field and Temperature Dependence of the Current-Voltage Characteristics of $Bi_2Sr_2Ca_2Cu_3O_{10+x}$/Ag Multifilamentary Tapes. A. Crisan, L. Miu, S. Popa and C. Beduz, *J. Supercond*. 10, 215-219 (1997).

16. Current-voltage characteristics of $Bi_2Sr_2Ca_2Cu_3O_{10+x}$/Ag multifilamentary tapes in zero applied magnetic field. A. Crisan, L. Miu, S. Popa, Y. Yang and C. Beduz, *Supercond. Sci. Technol*. 10, 298-303 (1997).

17. Current-voltage characteristics of long $Bi_2Sr_2Ca_2Cu_3O_{10}$/Ag multifilamentary tapes at different bending strains. M. K. Al-Mosawi, A. Crisan, C. Beduz, D. Phillips and P. Haldar, *Physica C*, 289, 63-69 (1997).

18. The influence of the structure on the electrical and magnetic properties of $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals. G. Aldica, A. Crisan, M. Velter-Stefanescu, S. Mandache and M. C. Bunescu, *J.Mater. Sci.* 32, 1195-1199 (1997).

19. Investigations of the zero-field (*a,b*)-plane conductivity of $YBa_2Cu_3O_{7-\delta}$ near the critical temperature. A. Crisan, S. N. Gordeev, S. Manton, A. P. Rassau, S. Popa, C. Beduz, P. A. J. de Groot, R. Gagnon, L. Taillefer, *Physica* C 309, 1-7 (1998).

20. $(BaCuO_2)_m/((Ca,Sr)CuO_2)_n$ superlattices grown by pulsed laser deposition: structural and electrical properties. G. Balestrino, A. Crisan, S. Martelucci, P. G. Medaglia, A. Paoletti, G. Petrocelli, in *Superconducting Superlattices II: Native and Artificial*, Eds. I. Bozovic and D. Pavuna, Proceedings of SPIE SPIE 98, San Diego, CA, Volume 3480, 37-43 (1998).

21. **Transport measurements, vortex dynamics and anisotropy in artificially layered $(BaCuO_2)_2/(CaCuO_2)_2$ superconducting films. A. Crisan, G. Balestrino, S. Lavanga, P. G. Medaglia, E. Milani, *Physica* C 313, 70-78 (1999).**

22. **The role of structural disorder in artificially layered high-temperature superconductors. G. Balestrino, A. Crisan, S. Lavanga, P. G. Medaglia, G. Petrocelli, A. A. Varlamov, *Phys. Rev.* B 60, 10504 - 10507 (1999).**

23. $[(BaCuO_2)_n/(CaCuO_2)_m]_N$ artificial superconducting superlattices. A. Crisan, P.G. Medaglia, G. Balestrino, *J. Optoel. Adv. Mater.* **2** (3), 215-234 (2000) (Review Article).

24. Current-Induced Unbinding of Thermally Created Vortex-Antivortex Pairs in Zero Magnetic Field. A. Crisan, Chapter 6 in 'Flux Pinning in High Temperature Superconductors', Vol. 31 of 'Studies of High Temperature Superconductors', pp. 183-216, Ed. A. Narlikar, Nova Science Publishers, New York (2000), ISBN 1-56072-790-X.

25. Synthesis of the $Ca_{0.45}Cu_{0.55}O$ peritectic phase using a mixture of nitrate powders. P. Badica, G. Aldica, G. Alexe, A. Crisan, *Mater. Lett.* 43, 180-184 (2000).

26. Superconducting properties from AC susceptibility and harmonic generation in $CuBa_2Ca_3Cu_4O_y$ bulk superconductors. A. Crisan, A. Iyo, Y. Tanaka, M. Hirai, M. Tokumoto, H. Ihara, *Physica C* 353, 227-240 (2001).

27. Fluctuation magnetoconductivity of BSCCO-2212 films in parallel magnetic field. G. Balestrino, A. Crisan, D.V. Livanov, S.I. Manokhin, E. Milani, *Physica C* 355, 135-139 (2001).

28. Some Superconducting Properties of the Inter-Domain Border of Melt-Textured $YBa_2Cu_3O_7$. A. Crisan, S.N. Gordeev, P.A.J. de Groot, C. Beduz, *Physica C* 355, 231-237 (2001).

29. The Influence of $BaZrO_3$ on the Magnetic Response of (Bi,Pb):2223 High-Temperature Superconductors. V. Mihalache, G. Aldica, S. Popa, P. Nita, and A. Crisan, *J.Supercond.* 14, 381-386 (2001).

30. Improvement of the Superconducting Transport Properties of $YBa_2Cu_3O_{7-\delta}$ by $BaZrO_3$ Doping. G. Aldica, I. Bradea, J. Jaklovszky, A. Crisan, *J. Supercond.* 14, 405-409 (2001).

31. The Influence of $BaZrO_3$ on the Magnetic Response of (Bi,Pb):2223 Superconducting System. V. Mihalache, G. Aldica, A. Crisan, *J. Mater. Sci. Lett.* 20, 889-891 (2001).

32. **Sputtered nanodots: A costless method for inducing effective pinning centers in superconducting thin films. A. Crisan, S. Fujiwara, J.C. Nie, A. Sundaresan, H. Ihara, *Appl. Phys. Lett.* 79, (27) 4547-4549 (2001).**

33. **Strong reduction of thermally activated flux jumps rate in superconducting thin films by nanodots induced pinning centers. A. Crisan, P. Badica, S. Fujiwara, J.C. Nie, A. Sundaresan, Y. Tanaka and H. Ihara, *Appl. Phys. Lett.* 80, 3566-3568 (2002).**

34. Decomposition of Ca:Cu=1:1 nitrate powder: thermal analysis and structural studies. P. Badica, G. Aldica, A. Crisan, *J. Mater. Sci.* 37, 585-594 (2002).

35. $(Cu,Tl)Ba_2Ca_3Cu_4O_x$ compositions: I. The influence of synthesis time and temperature on phase formation and evaporation-condensation mechanism. P. Badica, A. Iyo, A. Crisan, Y. Ishiura, A. Sundaresan and H. Ihara, *Supercond. Sci. Technol.* 15, 964-974 (2002).

36. $(Cu,Tl)Ba_2Ca_3Cu_4O_x$ compositions: II. Heating rate applied to synthesis of superconducting ceramics. P. Badica, A. Iyo, A. Crisan and H. Ihara, *Supercond. Sci. Technol.* 15, 975-982 (2002).

37. The influence of Tl and O content from the starting mixture on phase formation in (Cu,Tl)-1234 mixture. P. Badica, A. Crisan and H. Ihara, *Physica C*, 378-381, 683-687 (2002).

38. Magnetization and susceptibility studies on $BaZrO_3$-doped $YBa_2Cu_3O_{7-x}$ bulk superconductors. I Bradea, S. Popa, G. Aldica, V. Mihalache and A. Crisan, *J. Supercond.* 15, 237-242 (2002).

39. The effect of pinning centers in Zn-Doped $CuBa_2Ca_3Cu_4O_x$ high-temperature superconductors. A. Crisan, S.K. Agarwal, T. Koganezawa, R. Kuroda, K. Tokiwa, T. Watanabe, A. Iyo, Y. Tanaka, H. Ihara, *J. Phys. Chem.Sol.* 63, 1073-1076 (2002).

40. $TlSr_2CaCu_2O_y$ template for the growth of superconducting $Tl(Ba,Sr)_2Ca_2Cu_3O_y$ thin films on CeO_2 buffered sapphire. A. Sundaresan, A. Crisan, J.C. Nie, M.

Hirai, H. Asada, H. Kito, Y. Tanaka, and H. Ihara, *Supercond. Sci. Technol.* 15, 960-963 (2002).

41. Growth of $TlBa_2Ca_2Cu_3O_y$ superconducting thin film on CeO_2 buffered sapphire substrate. A. Sundaresan, J.C. Nie, M. Hirai, A. Crisan, S. Fujiwara, H. Asada, P. Badica, Y. Ishiura, H. Kito and H. Ihara, *Physica C*, 378-381, 1283-1286 (2002).

42. $Cu_mBa_{m+1}Ca_{n-1}Cu_nO_{2m+2n+1}$ superconducting thin film by self assembly epitaxy method. J.C. Nie, A. Sundaresan, M. Hirai, Y. Ishiura, P. Badica, A. Crisan and H. Ihara, *Physica C*, 378-381, 1278-1282 (2002).

43. Third harmonic susceptibility for studying the dissipation in heavy ion irradiated $(Cu,C)Ba_2Ca_3Cu_4O_{12-y}$ high temperature superconductor. A. Crisan, P. Badica, M. Hirai, H. Kito, A. Iyo, and Y. Tanaka, *Supercond. Sci. Technol.* 15, 1240-1243 (2002).

44. AC susceptibility and Higher Harmonics Studies of Heavy-Ions Irradiated $CuBa_2Ca_3Cu_4O_x$ Bulk Superconductor with Highest Irreversibility Field above Liquid-nitrogen Temperature. A. Crisan, A. Iyo, H. Kito, Y. Tanaka, M. Hirai, M. Sasase, S. Okayasu, H. Ihara, *Physica C*, 378-381, 112-117 (2002).

45. Superconducting properties of the heavy-ions and neutron irradiated $(Cu,C)Ba_2Ca_{n-1}Cu_nO_{2n+4-x}$ (n=3,4 and 5). H. Kito, A. Iyo, M. Hirai, A. Crisan, M. Tokumoto, S. Okayasu, M. Sasase and H. Ihara, *Physica C*, 378-381, 329-332 (2002).

46. Heavy-ion irradiation dependence of the superconducting properties of $(Cu,C)Ba_2Ca_3Cu_4O_{10.5-\delta}$. H. Kito, A. Iyo, A. Crisan, M. Hirai, M. Tokumoto, S. Okayasu, M. Sasase, H. Ihara and Y. Tanaka, *Physica C*, 388-389, 711-712 (2003).

47. Heavy-ions irradiation dependence of superconducting properties of the Cu-based $(Cu,C)Ba_2Ca_3Cu_4O_{11-\delta}$. H. Kito, A. Iyo, M. Hirai, A. Crisan, M. Tokumoto, S. Okayasu, M. Sasase, M. Sataka, H. Ihara, Y. Tanaka, *Physica* C 392-396, Part 1, 181-184 (2003).

48. Electron-doped superconductivity induced by oxygen vacancies in as-grown $Sr_{0.6}Ca_{0.4}CuO_{2-\delta}$ infinite-layer films. J.C. Nie, P. Badica, M. Hirai, A. Sundaresan, A. Crisan, H. Kito, N. Terada, Y. Kodama, A. Iyo, Y. Tanaka, H. Ihara, *Supercond. Sci. Technol.* 16, L1-L3 (2003).

49. Electron-doped superconductivity in $Sr_{1-x}Ca_xCuO_{2-\delta}$ infinite-layer thin films. J.C. Nie, P. Badica, M. Hirai, Y. Kodama, A. Crisan, A. Sundaresan, Y. Tanaka, and H. Ihara, *Physica C*, 388-389, 441-442 (2003).

50. Preparation of Tl-2212 and -1223 superconducting thin films and their microwave properties. A. Sundaresan, H. Asada, A. Crisan, J.C. Nie, H. Kito, A. Iyo, Y. Tanaka, M. Kusunoki, S. Ohshima, *Physica C*, 388-389, 473-474 (2003).

51. Preparation of Tl-2212 and Tl-1223 Superconductor Thin Films and Their Microwave Surface Resistance. A. Sundaresan, H. Asada, A. Crisan, J.C. Nie, H. Kito, A. Iyo, Y. Tanaka, M. Kusunoki, and S. Ohshima, *IEEE Trans. Appl. Supercond.,* 13 (2), 2913-2916 (2003).

52. Nanodots-Induced Pinning Centers in Thin Films: Effects on Critical Current Density, Activation Energy and Flux Jump Rate. A. Crisan, P. Badica, S.

Fujiwara, J.C. Nie, A. Sundaresan, A. Iyo, and Y. Tanaka, *IEEE Trans. Appl. Supercond.,* 13 (2), 3726-3729 (2003).

53. $TlBa_2Ca_2Cu_3O_y$ superconducting films on MgO with different morphologies. P. Badica, A. Sundaresan, A. Crisan, J.C. Nie, M. Hirai, S. Fujiwara, H. Kito and H. Ihara, *Physica C*, 383, 482-490 (2003).

54. Magnetic Properties of $Bi_{1.7}Pb_{0.4}Sr_{1.5}Ca_{2.5}Cu_{3.6}O_x/(LiF)_{(y)}$ superconducting system. V. Mihalache, G. Aldica, S. Popa, and A. Crisan, *Physica C*, 384, 451-457 (2003).

55. LiF addition to $(Cu,C)Ba_2Ca_3Cu_4Oy$ superconductor. P. Badica, A. Crisan, M. Hirai, A. Iyo, H. Kito, G. Aldica and Y. Tanaka, *Physica C* , 388-389, 395-396 (2003).

56. Tl-based superconducting phases obtained by evaporation-condensation technique. P. Badica, M. Hirai, H. Kito, A. Crisan, A. Iyo and Y. Tanaka, Proceedings of the 4^{th} *International Conference 'Science and Engineering of HTS Superconductivity', of the Forum on New Materials*, part of *CIMTEC2002*, Florence, Italy, 2002, in *Advances in Science and Technology*, **38**, *Science and Engineering of HTS Superconductivity IV*, p. 105-112, P. Vincenzini and S. Cerasara, Eds., Techna, Faenza, Italy (2003).

57. Intra- and inter-grain critical current density in (Cu,C):1234 superconductors. A. Crisan, P. Badica, M. Hirai, H. Kito, A. Iyo, and Y. Tanaka, *Physica C*, 388-389, 421-422 (2003).

58. **Vortex melting line and anisotropy of high-pressure-synthesized $TlBa_2Ca_2Cu_3O_{10-y}$ high-temperature superconductor from third-harmonic susceptibility studies. A. Crisan, A. Iyo and Y. Tanaka, *Appl. Phys. Lett.,* 83, 506-508 (2003).**

59. Hall probe imaging of local hysteresis inversion and negative remanent fields near the edge of a YBCO thin film. A. Crisan, A. Pross, R. G. Humphreys and S. Bending, *Supercond. Sci. Technol.,* 16, 695-698 (2003).

60. Vortex imaging and local magnetization studies in HTS by scanning Hall probe microscopy. A. Crisan, A. Pross, D. Cole, S. Bending, *Physica C* 408-410, 555-557 (2004).

61. Interacting crossing vortex lattices in the presence of quenched disorder. S.J. Bending, A.N. Grigorenko, I.A. Crisan, D. Cole, A.E. Koshelev, J.R. Clem, T. Tamegai, S. Ooi, *Physica* C 412-414, 372-378 (2004).

62. Flux Lenses in the Crossing Lattices Regime of Layered Superconductors. D. Cole, A. Crisan, S.J. Bending, T. Tamegai, K. van der Beek, M. Konczykovsky, *Physica* C 404, 99-102 (2004).

63. Comparison of magneto-optical imaging with other local magnetic probes. S.J. Bending, A. Brook, J.K. Gregory, I.A. Crisan, A. Pross, A.N. Grigorenko, A. Oral, F. Laviano and E. Mezzetti, in *Magneto-Optical Imaging*, T.H. Johansen and D.V. Shantsev (eds), NATO Science Series II. Mathematics, Physics and Chemistry, Kluver Academic Publishers, Vol. 142, pp. 11-18 (2004).

64. $(Cu,C)Ba_2Ca_3Cu_4O_x$-$(LiF)_y$: addition of LiF as an effective way to synthesize overdoped superconductors. P. Badica, A. Iyo, G. Aldica, H. Kito, A. Crisan, and Y. Tanaka, *Supercond. Sci. Technol.* 17, 430-437 (2004).

65. Anomalies of AC susceptibility losses in the doped $[Bi(Pb)]_2Sr_2Ca_2Cu_3O_x$ superconsuctor. V. Mihalache, G. Aldica, P. Badica, and A. Crisan, *Supercond. Sci. Technol.* 17, 724-730 (2004).

66. Enhancement of critical current density in $YBa_2Cu_3O_{7-\delta}$ thin films grown using PLD on YSZ(001) surface modified with Ag nanodots. M. Ionescu, A.H. Li, Y. Zhao, H.K. Liu and A. Crisan, *J. Phys. D: Appl. Phys.* 37, 1824-1828 (2004).

67. **Anisotropic vortex channelling in $YBa_2Cu_3O_{7-\delta}$ thin films with ordered antidot arrays. A. Crisan, A. Pross, D. Cole, S.J. Bending, R. Wördenweber, P. Lahl, E.H. Brandt, *Phys. Rev.* B 71, 144504 (2005).**

68. **Flux structures in mesoscopic $YBa_2Cu_3O_{7-\delta}$ discs. A. Crisan, S.J. Bending, A. Pross, A. Aziz, A.N. Grigorenko, R.G. Humphreys, *Supercond. Sci. Technol.* 18, 207 (2005).**

69. **Observation of interacting crossing vortex lattices in $Bi_2Sr_2CaCu_2O_{8+\delta}$ thin films. A. Crisan, S. J. Bending, S. Popa, Z. Z. Li, H. Raffy, *Phys. Rev.* B 72, 214509 (2005).**

70. Second-generation quantum-well sensors for room-temperature scanning Hall probe microscopy. A. Pross, A.I. Crisan, S.J. Bending, V. Mosser, M. Konczykowski, *J. Appl. Phys.* 97, 096105 (2005).

71. **Anomalous vortex melting line in the two-component superconductor (Cu, C)$Ba_2Ca_3Cu_4O_{10+\delta}$. A. Crisan, Y. Tanaka, A. Iyo, L. Cosereanu, K. Tokiwa, T. Watanabe, *Phys. Rev.* B 74, 184517 (2006).**

72. Self-assembling nanotechnology of Au nano-dots for superconducting films and devices. A. Crisan, S. Popa, R. Woerdenweber, E. Hollmann, R. Kutzner, T.W. Button, J.S. Abell. *Proceedings of The 5th International Conference on Advanced Manufacturing Technologies, ICAMaT2007*, 12-14 July 2007, Sibiu, Romania, pp. 427-430, AGIR Publishing House, ISSN 1243-3162 (2007).

73. **Coexistence of Superconductivity and Antiferromagnetism in $HgBa_2Ca_4Cu_5O_y$: Multi-harmonic Susceptibility and Vortex Dynamics Study. A. Crisan, Y Tanaka, A. Iyo, D. D. Shivagan, P. M. Shirage, K. Tokiwa, T. Watanabe, L. Cosereanu, T. W. Button, J. S. Abell, *Phys. Rev. B,* 76, 212508 (2007).**

74. **Anomalous AC susceptibility response of (Cu,C)$Ba_2Ca_2Cu_3O_y$: Experimental indication of two-component vortex matter in multi-layered cuprate superconductors. A. Crisan, Y. Tanaka, D. D. Shivagan, A. Iyo, L. Cosereanu, K. Tokiwa, T. Watanabe, *Jap. J. Appl. Phys.* 46, L451-L453 (2007).**

75. Interpretation of abnormal ac loss peak based on Vortex-Molecule model for a multicomponent cuprate superconductor. Y. Tanaka, A. Crisan, D.D. Shivagan, A. Iyo, K. Tokiwa, T. Watanabe. *Jap. J. Appl. Phys.* 46, 134-145 (2007).

76. Vortex molecule and i-soliton studies in multilayer cuprate superconductors. D. D. Shivagan, A. Crisan, P.M. Shirage, A. Sundaresan, Y. Tanaka, A. Iyo, K. Tokiwa, T. Watanabe, N. Terada, *Journal of Physics: Conference Series*, 97, 012212 (2008).

77. AC-Susceptibility study on vortex-molecule lattice in supermultilayer cuprate $HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$ (n = 14). D. D. Shivagan, P. M. Shirage, A. Crisan, Y. Tanaka, A. Iyo, K. Tokiwa, T. Watanabe, N. Terada, *Physica C: Superconductivity and its Applications,* 468, 1281-1286 (2008).

78. Phase diagram of a lattice of vortex molecules in multicomponent superconductors and multilayer cuprate superconductors. Y. Tanaka, D. D. Shivagan, A. Crisan, A. Iyo, P.M. Shirage, K. Tokiwa, T. Watanabe, N. Terada, *Superconductor Science and Technology*, **21**, 085011 (17pp) (2008).

79. Manipulation of pancake vortices by rotating a Josephson vortex lattice. A. Crisan, S. J. Bending, T. Tamegai, *Supercond. Sci. Technol.,* 21, 015017 (2008).

80. **Magnetically coupled pancake vortex molecules in $HgBa_2Ca_{n-1}Cu_nO_y$ ($n \geq$ 6). A. Crisan, A. Iyo, Y. Tanaka, H. Matsuhata, D.D. Shivagan, P.M. Shirage, K. Tokiwa, T. Watanabe, T.W. Button, J.S. Abell, *Phys. Rev. B,* 77, 144518 (2008).**

81. Pancake-vortex molecules in $HgBa_2Ca_{n-1}Cu_nO_y$ ($n \geq 6$) superconductors. A. Crisan, A. Iyo, Y. Tanaka, H. Matsuhata, D.D. Shivagan, P.M. Shirage, K. Tokiwa, T. Watanabe, T.W. Button, J.S. Abell, *Physica C: Superconductivity and its Applications,* **468**, 714-717 (2008).

82. Vortex Dynamics in Hg-based Multi- and Super-Multi-Layered Cuprates. A. Crisan, Y. Tanaka, A. Iyo, D.D. Shivagan , P.M. Shirage, T.W. Button, J.S. Abell, K. Tokiwa, T. Watanabe, *Journal of Physics: Conference Series*, **97**, 012013 (2008).

83. Critical current densities and irreversibility fields of a $HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$ sample containing n = 6–15 phases. P.M. Shirage, A. Iyo, D.D. Shivagan, A. Crisan, Y. Tanaka, Y. Kodama, H. Kito, *Physica C: Superconductivity and its Applications,* **468**, 1287-1290 (2008).

84. Superconductivity at 108 K in the simplest non-toxic double-layer cuprate of $Ba_2Ca_3Cu_4O_8(O, F)_2$. P.M. Shirage, D.D. Shivagan, A. Crisan, Y. Tanaka, Y. Kodama, H. Kito and A. Iyo, *Journal of Physics: Conference Series*, **97**, 012163 (2008).

85. Critical current densities and irreversibility fields of new high-T_c $Ba_2Ca_3Cu_4O_8(O, F)_2$ superconductor. P.M. Shirage, D.D. Shivagan, A. Crisan, Y. Tanaka, Y. Kodama, H. Kito and A. Iyo, *Physica C: Superconductivity and its Applications,* **468**, 773-776 (2008).

86. Vortex melting line and dimensional crossover in $Ba_2Ca_{n-1}Cu_nO_{2n}(O_{1-y}, Fy)_2$ cuprate superconductors. D. D. Shivagan, P. M. Shirage, A. Crisan, Y. Tanaka, A. Iyo, Y. Kodama, K. Tokiwa, T. Watanabe, N. Terada, N. Hamada, *Physica C: Superconductivity and its Applications,* **468**, 749-752 (2008).

87. Vortex melting line and anisotropy of a $Ba_2Ca_3Cu_4O_8(O_{1-y}F_y)_2$ multilayered superconductor. D. D. Shivagan, P. M. Shirage, A. Crisan, Y. Tanaka, A. Iyo, Y. Kodama, K. Tokiwa, T. Watanabe, N. Terada, and N. Hamada, *Superconductor Science and Technology*, **21**, 095002 (7pp) (2008).

88. Thermally-induced self-assembling nanotechnology of gold nano-dots on CeO2-buffered sapphire for superconducting films. A. Crisan, R. Woerdenweber,

E. Hollmann, R. Kutzner, T.W. Button, J.S. Abell, *J. Optoel. Adv. Mater.,* **10**, 1370-1373 (2008).

89. Artificial pinning centres in $YBa_2Cu_3O_{7-\delta}$ Thin Films by $Gd_2Ba_4CuWO_y$ nanophase inclusions, M. M. Awang Kechik, P. Mikheenko, A. Sarkar, V. S. Dang, N. Hari Babu, D. A. Cardwell, J. S. Abell and A. Crisan, *Superconductor Science and Technology*, **22**, 034020 (5pp) (2009).
90. **Critical Current Density and Pinning Potential in $YBa_2Cu_3O_{7-\delta}$ Thick Films Ablated from a $BaZrO_3$ – Doped Nanocrystalline Target, A. Crisan, M.M. Awang Kechik, P. Mikheenko, V.S. Dang, J.S. Abell, P. Paturi, H. Huhtinen, *Superconductor Science and Technology*, 22, 045014 (5pp) (2009).**
91. All-self-assembled MgO nanorods and nanowires grown on Au-decorated MgO substrates by pulsed laser deposition, A. Crisan, J.L. Tanner, P. Mikheenko, J.S. Abell, *Optoelectronics and Advanced Materials – Rapid Communications*, **3**, 231-235 (2009).
92. Vortex molecule, fractional flux quanta, and interband phase difference soliton in multi-band superconductivity and multi-component superconductivity, Y. Tanaka, D.D. Shivagan, A. Crisan, A. Iyo, P.M. Shirage, K. Tokiwa, T. Watanabe, N. Terada, *Journal of Physics: Conference Series*, **150**, 052267 (2009).
93. Ambiguity in the statistics of single component winding vortex in a two-band superconductor, Y Tanaka and A Crisan, *Physica B: Condensed Matter*, **404**, 1033-1039 (2009).
94. *c*-Axis correlated extended defects and critical current in $YBa_2Cu_3O_x$ films grown on Au and Ag-nano dot decorated substrates, P. Mikheenko, A. Sarkar, V.-S. Dang, J. L. Tanner, J. S. Abell, and A. Crisan, *Physica C: Superconductivity and its Applications,* 469, 798-804 (2009).
95. **Pinning centers induced in YBCO films by nano-dots in substrate decoration and quasi-superlattice approaches, P. Mikheenko, A. Sarkar, V.-S. Dang, J. L. Tanner, M.M. Awang Kechik, J. S. Abell, and A. Crisan, *IEEE Transactions on Applied Superconductivity,* 19(3), 3491-3494 (2009).**
96. Improvement of pinning force and critical current density in thick $YBa_2Cu_3O_{7-\delta}$ films grown on $SrTiO_3$ substrates decorated with $LaNiO_3$ nanodots, A. Crisan, A. Sarkar, P. Mikheenko, V.S. Dang, M.M. Awang Kechik, J.S. Abell, *Journal of Superconductivity and Novel Magnetism* **22**, 631-636 (2009).
97. Enhancing critical current in YBCO thick films: substrate decoration and quasi-superlattice approach, A. Sarkar, P. Mikheenko, V.S. Dang, J. S. Abell, and A. Crisan, *Physica C: Superconductivity and its Applications,* **469** (15-20), 1550-1553 (2009).
98. Phase diagram of a lattice of pancake vortex molecules, Y. Tanaka, A. Crisan, D.D. Shivagan, A. Iyo, P.M. Shirage, K. Tokiwa, T. Watanabe, N. Terada, *Physica C: Superconductivity and its Applications,* **469** (15-20), 1129-1131 (2009).
99. $YBa_2Cu_3O_{7-x}$ thin films by citrate-based non-fluorine precursor, W. Cui, P. Mikheenko, L.M. Yu, T.W. Button, J.S. Abell and A. Crisan, *Journal of Superconductivity and Novel Magnetism* **22**, 811-815 (2009).

100. Pinning potential in thick $PrBa_2Cu_3O_x/YBa_2Cu_3O_{7-\delta}$ quasi-multilayers, A. Crisan, V.S. Dang, P. Mikheenko, Y.Y. Tse, A. Sarkar, J. Bowen, J.S. Abell, *Physica C: Superconductivity and its Applications,* **470**, 55-60 (2010).

101. Critical current density and pinning in Ag/YBa2Cu3Ox and PrBa2Cu3Oy/YBa2Cu3Ox multilayers, V. S. Dang, P. Mikheenko, A. Sarkar, M. M. Awang Kechik, J S Abell1 and A Crisan, *J. Phys.: Conf. Ser.* **234,** 012010 (2010).

102. Self-assembled artificial pinning centres in thick YBCO superconducting films, P Mikheenko, J S Abell, A Sarkar, V S Dang, M M Awang Kechik, J L Tanner, P Paturi, H Huhtinen, N Hari Babu, D A Cardwell and A Crisan, *J. Phys.: Conf. Ser.* **234,** 022022 (2010).

103. Artificial pinning in thick YBCO films: Pinning potential and c-axis correlation, A. Crisan, P. Mikheenko, A. Sarkar, V. S. Dang, M. M. Awang Kechik, J. S. Abell, P. Paturi, H. Huhtinen, *Physica C: Superconductivity and its Applications,* **470**, 840-843 (2010).

104. Increased critical current density and pinning in thick Ag/YBa2Cu3O7-x multilayers, V. S. Dang, P. Mikheenko, A. Sarkar, M. M. Awang Kechik, J S Abell1 and A Crisan, *Physica C: Superconductivity and its Applications,* **470**, 1238-1241 (2010).

105. Topological structure of the interband phase difference soliton in two-band superconductivity, Y. Tanaka, A. Iyo, K. Tokiwa, T. Watanabe, A. Crisan, A. Sundaresan, N. Terada, *Physica C: Superconductivity and its Applications,* **470**, 1010-1012 (2010).

106. **Nanodots induced columnar growth of $YBa_2Cu_3O_x$ films, P. Mikheenko, J.L. Tanner, J. Bowen, A. Sarkar, V.-S. Dang, J.S. Abell, A. Crisan, *Physica C: Superconductivity and its Applications*, 470, (Suppl. 1), S234-S236 (2010).**

107. Topology of two-band superconductors, Y. Tanaka, A. Iyo, K. Tokiwa, T. Watanabe, A. Crisan, A. Sundaresan, N. Terada, *Physica C: Superconductivity and its Applications,* **470,** (Suppl. 1), S966-S967 (2010).

108. Improved critical current densities in thick $YBa_2Cu_3O_{7-x}$ multilayer films interspaced with non-superconducting $YBa_2Cu_3O_x$ nanodots, A. Sarkar, V.S. Dang, P. Mikheenko, M.M Awang Kechik, J.S. Abell, A. Crisan, *Thin Solid Films,* **519**, 876-879 (2010).

109. **Integrated nanotechnology of pinning centres in $YBa_2Cu_3O_x$ films. P. Mikheenko, V.-S. Dang, Y.Y. Tse, M. M. Awang Kechik, P. Paturi, H. Huhtinen, Y. Wang, J. S. Abell and A. Crisan, *Superconductor Science and Technology*, 23, 125007 (2010).**

110. Combination of Ag Substrate Decoration with Introduction of BaZrO3 Nano-Inclusions for Enhancing Critical Current Density of YBa2Cu3O7 Films, V. S. Dang, A. Sarkar, P. Mikheenko, M. M. Awang Kechik, J. S. Abell, P. Paturi, H. Huhtinen, A. Crisan, *Journal of Superconductivity and Novel Magnetism*, **24** (5), 505-509 (2011).

111. Nano Techniques for Enhancing Critical Current in Superconducting YBCO Films, P. Mikheenko, V.S. Dang, M.M. Awang Kechik , Y. Wang, A. Sarkar, J.L.

Tanner, J. S. Abell, A. Crisan, *Journal of Superconductivity and Novel Magnetism* **24** (5), 1059-1064 (2011).

112. Improved Critical Current Densities in $YBa_2Cu_3O_{7-\delta}$ Multilayer Films Interspaced with Palladium Nanodots, A. Sarkar, P. Mikheenko, V.S. Dang, M.M. Awang Kechik, J. S. Abell, A. Crisan, *Journal of Superconductivity and Novel Magnetism* **24** (5), 173-177 (2011).

113. Exotic Vortex Matter: Pancake Vortex Molecules and Fractional-Flux Molecules in Some Exotic and/or Two-Component Superconductors, A. Crisan, Y. Tanaka, A. Iyo, *Journal of Superconductivity and Novel Magnetism* **24** (5), 1-6 (2011).

114. **Synergetic pinning centres in $YBa_2Cu_3O_x$ films through a combination of Ag nano-dot substrate decoration, Ag/YBCO quasi-multilayers, and the use of $BaZrO_3$-doped target, P. Mikheenko, V.-S. Dang, M. M. Awang Kechik, A. Sarkar, P. Paturi, H. Huhtinen, J. S. Abell and A. Crisan, *IEEE Trans. Appl. Supercond.* 21 (3) 3184-3188 (2011).**

115. 'Beautiful' unconventional synthesis and processing technologies of superconductors and some other materials. P.Badica, A. Crisan, G. Aldica, K. Endo, H. Borodianska, K. Togano, S. Awaji, K. Watanabe, Y. Sakka, O. Vasylkiv, *Science and Technology of Advanced Materials*, **12**, 013001 (2011).

116. **Intermittent trapping of a liquid-like vortex state visualized by scanning Hall probe microscopy, A. Crisan, S.J. Bending, Z.Z. Li, H. Raffy, *Superconductor Science and Technology*, 24, 115001 (2011).**

117. Domains in multiband superconductors, Y. Tanaka, T. Yanagisawa, A. Crisan, P.M. Shirage, A. Iyo, K. Tokiwa, T. Nishio, A. Sundaresan, N. Terada, *Physica C: Superconductivity and its Applications,* **471,** 747-750 (2011).