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11 Ilguard boundary offect on cohoronous in two band queense ductage $\frac{1}{12}$ Unusual boundary effect on coherency in two-band superconductors $\frac{1}{78}$

13 79 14 80 Artjom Vargunin ^{a, b}, Küllike Rägo ^a, Teet Örd ^a and a set of the s

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¹⁹ ARTICLE INFO ABSTRACT ⁸⁵

28 minimum displacement of the contract of the *Article history:* Received 12 April 2017 Received in revised form 1 August 2017 Accepted 3 August 2017 Available online xxxx Communicated by L. Ghivelder *Keywords:* Multiband superconductivity

29 provinity to the contract of the contract o 30 96 Ginzburg–Landau equation Superconducting correlations Proximity

²¹ Article history: **Example 21** Article history: **Example 20** We demonstrate that restoration of two-band superconductivity near the surface of the system is ⁸⁷ 22 Received 12 April 2017 governed by length scales which are drastically different from correlation lengths. Similar to the one- 88 23 Band case, one of the characteristic lengths diverges at critical temperature *T_c*, while another one shows 89 24 Available online xxx
Available online xxx
Available online xxx ²⁵ Communicated by L. Ghivelder **and the summand correlation lengths in the bulk state, where the divergence at** T_{c+} **is removed by arbitrary 91** 26 92 weak interband coupling. The peculiarity can be manifested in proximity sandwich where *T*c⁺ becomes ₂₇ *Keywords:* examplection point for critical temperature being a function of superconducting layer thickness.

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1. Introduction

37 Becently discovered multiband superconductors – Fe-based correlation lengths [\[16–18\]](#page--1-0) which results in the multiscale physics 103 38 compounds and MgB₂ – demonstrate properties beneficial for manifesting, in particular, in the vortex core stretching [\[19\]](#page--1-0) and 104 39 various applications [1–4]. An implementation of these materials unusual magnetic response [\[20\].](#page--1-0) The subject provoked discussion 105 40 requires superconducting samples of reduced dimensionality. The $[21-23]$ which revealed strong discrepancy between correlation $[106]$ ⁴¹ fabrication and characterization of such systems is nowadays ac- lengths driving bulk asymptotic behaviour of gap functions and 107 Recently discovered multiband superconductors – Fe-based compounds and $MgB₂$ – demonstrate properties beneficial for various applications $[1-4]$. An implementation of these materials requires superconducting samples of reduced dimensionality. The fabrication and characterization of such systems is nowadays actively investigated [\[5–7\].](#page--1-0)

¹⁰⁹ The reduction of the sample thickness considerably affects su-
¹⁰⁹ normal boundary. This peculiarity of multiband systems did not at-44 perconducting properties. The critical temperature usually shows tract proper attention whereas it seems to be very important for 110 45 gradual decrease from the bulk value as film becomes thinner $\left[8\right]$. proximity systems where physics near interface plays crucial role 111 ⁴⁶ This behaviour can be explained by the appearance of degraded Multiscale effect on proximity phenomenon was not systematically ¹¹² 47 non-superconducting layers on the surface giving rise to proxim-
47 analyzed as well ⁴⁸ ity effect. Striking example of proximity phenomenon is surface-
¹¹⁴ 49 induced superconductivity in ultrathin FeSe films grown on SrTiO₃ two-band superconductor near its boundary where system is af The reduction of the sample thickness considerably affects susubstrate [\[9\].](#page--1-0)

51 Hybrid structures involving multiband superconductors demon-
117 52 strate number of non-trivial properties. Proximity to a supercon- $\frac{1}{2}$ ductor with a lower transition temperature is able to enhance the construction of the surface and find that the set due of the set of 54 multiband superconductivity [\[10\].](#page--1-0) Contrariwise, conventional su-
120 55 perconductivity can be suppressed by contact with nominally actually deviated from the bulk conterparts. The behaviour is in 121 56 stronger two-gap superconductor [\[11\].](#page--1-0) The interface of multiband subsequences to the one-band superconductivity inoder, where $\frac{122}{2}$ 57 superconductor can reverse interband phase $\left[12\right]$ or even harbour
 $\frac{323}{12}$ or even harbour contentions in all alternative boundary, meaning that same $\frac{123}{12}$ 58 the time-reversal-symmetry-breaking state [\[13,14\].](#page--1-0) The religion of the drives superconductivity both hear system surface and the 124

59 The textbook knowledge on proximity effect in conventional The Durk. We demonstrate that surface-driven modifications or $_{125}$ 60 superconductors tells that evolution of superconductivity near in- Superconductivity correlations can result in hon-trivial effects in $_{126}$

64 130 <http://dx.doi.org/10.1016/j.physleta.2017.08.010>

35 **1. Introduction 1. Introduction 101 terface is governed by correlation length [\[15\].](#page--1-0) Recently, it was es-** 101 36 102 tablished that multicomponent superconductors contain multiple 42 tively investigated [5–7]. The same state of the state of superconductivity near the state of superconductivity near 108 tract proper attention whereas it seems to be very important for proximity systems where physics near interface plays crucial role. Multiscale effect on proximity phenomenon was not systematically analysed as well.

50 substrate [9].
- The Mathematic and multiscale the interplay between proximity effect and multiscale the interplay between proximity effect and multiscale 61 127 normal/two-band superconductor binary systems. This peculiarity 62 128 should be taken into account when tuning multiband supercon-63 63 **6** *E-mail address: bh@ut.ee* (A. Vargunin). The control of the control of ductivity for practical applications. In this contribution, we investigate coherency properties of two-band superconductor near its boundary, where system is afphysics (no time-reversal symmetry breakdown is involved). We calculate characteristic length scales for superconductivity correlations in the vicinity of the surface and find that they are drastically deviated from the bulk counterparts. The behaviour is in strong contrast to the one-band superconductivity model, where coherency is not affected by the boundary, meaning that same length scale drives superconductivity both near system surface and in the bulk. We demonstrate that surface-driven modifications of superconductivity correlations can result in non-trivial effects in

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2. Formalism

3 69 Various approaches exist to describe mutual influence of the 4 subsystems in contact. Microscopic models, such as McMillan tun- $\epsilon_1 = \cos \varphi_-\epsilon_- - \sin \varphi_+\epsilon_+$, ⁵ neling model [\[24\]](#page--1-0) and Green's functions approach [\[25\]](#page--1-0) are power-
⁵ $\epsilon_2 = \sin \omega_-\epsilon_+ + \cos \omega_+\epsilon_+$. 6 72 ful tools for analysis of proximity effects. Below we discuss phe-[\[26\].](#page--1-0)

10 76 We start with the Ginzburg–Landau equations for clean *s*-wave ⁷⁸ taking into account Josephson tunneling between bands, the free-13 energy density $F = \sum_{\alpha} F_{\alpha}$ is given by energy density $F = \sum_{\alpha} F_{\alpha}$ is given by

$$
F_{\alpha} = a_{\alpha} |\delta_{\alpha}|^2 + b_{\alpha} |\delta_{\alpha}|^4 / 2 - c \delta_{\alpha} \delta_{3-\alpha}^* + K_{\alpha} |\nabla \delta_{\alpha}|^2,
$$
\n(1) In the absence of interband coupling, coherency in each con-
denote is characterized by length scale, as respectively.

where expansion coefficients read as [\[27\]](#page--1-0)

$$
a_{\alpha} = W_{3-\alpha,3-\alpha}/\text{det}\hat{W} - \rho_{\alpha} \ln[0.13\hbar\omega_{D}/(k_{B}T)],
$$

\n
$$
b_{\alpha} = 0.11\rho_{\alpha}/(k_{B}T)^{2}, \qquad K_{\alpha} = b_{\alpha}\hbar^{2}v_{F\alpha}^{2}/6,
$$
\n(2)

22 and $c = W_{12}/\text{det}W$. Here $W_{\alpha\alpha} > 0$ and $W_{12} = W_{21}$ are matrix always finite [31,32]. ₂₃ elements for intraband and interband pair-transfer interactions, ρ_α in addition, bulk state is characterized by separate length due separate length due 15 the density of states at the Fermi level, $v_{F\alpha}$ is the Fermi velocity to interband phase variation $(C_1 + C_2)\psi = \psi''$. Here $C_1 + C_2$ is di-
in the relevant hand and here is the Debye energy out off. Note $_{25}$ in the relevant band, and *h* $\omega_{\rm D}$ is the Debye energy cut-off. Note mensionless mass of the Leggett mode. that in this model det $W > 0$ is assumed. elements for intraband and interband pair-transfer interactions, *ρα* is the density of states at the Fermi level, $v_{F\alpha}$ is the Fermi velocity

 $_{27}$ Spatial variation of gap fields δ _α is governed by the Ginzburg– (2.2. Asymptotic near boundary 28 94 Landau equations

$$
a_{\alpha}\delta_{\alpha} - c\delta_{3-\alpha} + b_{\alpha}|\delta_{\alpha}|^2 \delta_{\alpha} = K_{\alpha}\nabla^2 \delta_{\alpha},\tag{3}
$$

31 supplemented by relevant boundary condition. Following de Gen-chassile and some that we have become mixed. Next we as-
31 supplemented by relevant boundary condition. Following de Gen-chassile Sans density and phase mod 32 nes [\[28\],](#page--1-0) we require $\mathbf{n}\nabla\delta_{\alpha} = \sum_{\beta} \tau_{\alpha\beta}\delta_{\alpha}$ at the boundary of a su-
interval interface suppresses superconductivity as for the border of a su-
interval interval in the parameter of the border of the bord 33 99 perconductor, where **ⁿ** is unit vector normal to the surface and *τ*ˆ 34 is matrix of inverse extrapolation lengths whose coefficients satisfy symmetry breakdown taking ψ mod $\pi = 0$. Then the Ginzburg- 100 $\tau_{\alpha\alpha} = \tau_{\alpha\alpha}^*$ and $\tau_{21} = \tau_{12}^* K_1/K_2$. To preserve time-reversal symme-

101 npper sign corresponds to $\psi = 0$. We decouple bands using mixed and the set of the set 36 try on the level of boundary condition, we take $\tau_{12} = \tau_{12}^*$. upper sign corresponds to $\psi = 0$. We decouple bands using mixed 102 try on the level of boundary condition, we take $\tau_{12} = \tau_{12}^*$.

³⁷ Extrapolation lengths entering matrix *τ*̂ characterize the inter-
- <u>modes</u> ³⁸ action between superconductor and ambient environment and, in $f_1 = \cos \theta$ f $\sin \theta$, f (7) (7) (104) 39 particular, the penetration of order parameters into it. Generally, $\frac{1}{1-\cos\theta}$ = $\frac{1}{2}$ = $\$ ⁴⁰ extrapolation length can vary in wide limits ranging from nega- $f_2 = \sin \theta_- f_- + \cos \theta_+ f_+$. 106 ⁴¹ tive values (contact with nominally stronger superconductor) until $\sigma_{\rm tot}$ tange and $\sigma_{\rm tot}$ and $\sigma_{\rm tot}$ in $\sigma_{\rm tot}$ 42 infinity (neighbourship with vacuum or insulator) Extrapolation by dating C_1 and $C_2 = C_2$ and $C_3 = C_1$ $C_2 = C_3$ in $C_3 = C_4$ in $C_4 = C_5$ in $C_5 = C_6$ in $C_6 = C_7$ in $C_7 = C_8$ in $C_8 = C_8$ in $C_9 = C_8$ in $C_9 = C$ ⁴³ length depends also on fabrication parameters [29] and applied $\frac{1}{4} \alpha - \frac{2}{2} \alpha_0$, we obtain $J_{\pm} = 2 J_{\pm}/\frac{1}{4} \pm 2$ with 44 field [30] **110 120 120 120 120 120 120 120 120 120 120 120 120** infinity (neighbourship with vacuum or insulator). Extrapolation length depends also on fabrication parameters [\[29\]](#page--1-0) and applied field [\[30\].](#page--1-0)

⁴⁶ tering equation (3). By introducing bulk gaps $|\Delta_{\alpha}|$ and length Dimensionless length scales of the problem are given by $\gamma_{\pm} = \frac{112}{140}$ 47 $\sqrt{2}$ $\sqrt{11}$ 1 $\sqrt{11}$ 1 $\sqrt{11}$ 1 $\sqrt{11}$ $\sqrt{11$ $\lambda = \Phi/\sqrt{8\pi \sum_{\alpha} K_{\alpha} |\Delta_{\alpha}|^2}$, where $\Phi = \hbar c/(2e)$, we scale distances $\sqrt{|\Gamma_{+}|}$. The latter ones define the healing of two-band supercon-
distribution also to its interfere α_4 as *X* = *λx* and order parameters as $\delta_\alpha = |\Delta_\alpha| f_\alpha e^{i\psi_\alpha}$. By assum-
Dimensional lengths γ_α bave very unusual properties [34] di-
as *X* = *λx* and order parameters as $\delta_\alpha = |\Delta_\alpha| f_\alpha e^{i\psi_\alpha}$. By assum- 50 ing that gap fields depend only on a distance *x* to the interface,
 $\frac{1}{16}$ interface $\frac{1}{16}$ interface $\frac{1}{16}$ interface $\frac{1}{16}$ is the term of $\frac{1}{51}$ equation (3) can be written in the form $\frac{1}{51}$ and $\frac{1}{51}$ expectively at the temperatures $t \in S$ and $t \in S$

$$
\mathcal{A}_{\alpha} f_{\alpha} + G_{\alpha}^2 f_{\alpha} \psi'^2 - \mathcal{C}_{\alpha} f_{3-\alpha} \cos \psi + \mathcal{B}_{\alpha} f_{\alpha}^3 = f_{\alpha}''
$$
\n
$$
\mathcal{A}_{\alpha} f_{\alpha} + G_{\alpha}^2 f_{\alpha} \psi'^2 - \mathcal{C}_{\alpha} f_{3-\alpha} \cos \psi + \mathcal{B}_{\alpha} f_{\alpha}^3 = f_{\alpha}''
$$
\n
$$
\mathcal{A}_{\alpha} f_{\alpha} + G_{\alpha}^2 f_{\alpha} \psi'^2 - \mathcal{C}_{\alpha} f_{3-\alpha} \cos \psi + \mathcal{B}_{\alpha} f_{\alpha}^3 = f_{\alpha}''
$$
\n
$$
\mathcal{A}_{\alpha} f_{\alpha} + G_{\alpha}^2 f_{\alpha} \psi'^2 - \mathcal{C}_{\alpha} f_{3-\alpha} \cos \psi + \mathcal{B}_{\alpha} f_{\alpha}^3 = f_{\alpha}''
$$
\n
$$
\mathcal{A}_{\alpha} f_{\alpha} + G_{\alpha}^2 f_{\alpha} \psi'^2 - \mathcal{C}_{\alpha} f_{3-\alpha} \cos \psi + \mathcal{B}_{\alpha} f_{\alpha}^3 = f_{\alpha}''
$$
\n
$$
\mathcal{A}_{\alpha} f_{\alpha} + G_{\alpha}^2 f_{\alpha} \psi'^2 - \mathcal{C}_{\alpha} f_{3-\alpha} \cos \psi + \mathcal{B}_{\alpha} f_{\alpha}^3 = f_{\alpha}''
$$
\n
$$
\mathcal{A}_{\alpha} f_{\alpha} + G_{\alpha}^2 f_{\alpha} \psi'^2 - \mathcal{C}_{\alpha} f_{3-\alpha} \cos \psi + \mathcal{B}_{\alpha} f_{\alpha}^3 = f_{\alpha}''
$$
\n
$$
\mathcal{A}_{\alpha} f_{\alpha} + G_{\alpha}^2 f_{\alpha} \psi'^2 - \mathcal{C}_{\alpha} f_{3-\alpha} \cos \psi + \mathcal{B}_{\alpha} f_{\alpha}^3 = f_{\alpha}''
$$
\n
$$
\mathcal{A}_{\alpha} f_{\alpha} + G_{\alpha}^2 f_{\alpha} \psi'^2 - \mathcal{C}_{\alpha} f_{3-\alpha} \cos \psi + \mathcal{B}_{\alpha} f_{\alpha}^3 = f_{\alpha}''
$$
\n
$$
\mathcal{
$$

56 where $\psi = \psi_1 - \psi_2$, $\mathcal{A}_\alpha = a_\alpha \lambda^2 / K_\alpha$, $\mathcal{B}_\alpha = b_\alpha |\Delta_\alpha|^2 \lambda^2 / K_\alpha$, $\mathcal{C}_\alpha =$ it is a point where γ ₋λ becomes infinitely large. Smaller tem-
122 57 c|Δ_{3−*α*}|λ²/(K_α|Δ_α) and *G*_α = C_α $f_{3-α}^2$ /($\sum_{\beta} C_{\beta} f_{3-β}^2$). Spatial de-
perature T_{c+} defines singularity of γ₊λ. This point has physical 123 58 pendence of the phases generates supercurrent in the bands, how- meaning only for vanishing interband interaction when T_{c} ap- 124 59 ever, net supercurrent is vanishing. Bulk gaps $|\Delta_{\alpha}|$ are defined by proach critical temperatures for non-interacting condensates, $T_{c1,2}$, 125 60 Eq. (4) in homogeneous limit, where $f_\alpha = 1$ and $\psi = 0$ provided respectively. ⁶¹ that $W_{12} > 0$. W_{11} is the state of two-band superconductor is characterized V_{12} that $W_{12} > 0$.

2.1. Asymptotic near bulk state

Deviations $\epsilon_{\alpha} = 1 - f_{\alpha}$ from the bulk state determined by

1 **2. Formalism by** $(A_\alpha + 3B_\alpha)\epsilon_\alpha - C_\alpha\epsilon_{3-\alpha} = \epsilon_\alpha^{\prime\prime}$. We introduce mixing angles φ_\pm 67 2 and new fields ϵ_{\pm} as follows 68

$$
\epsilon_1 = \cos \varphi_-\epsilon_- - \sin \varphi_+\epsilon_+, \tag{5}
$$

$$
\epsilon_2 = \sin \varphi_-\epsilon_- + \cos \varphi_+\epsilon_+.
$$

7 anomenological description based on the Ginzburg–Landau formal-
 \int Choice $C_1 \tan \varphi = C_2 \tan \varphi = 2(\xi^2 - \xi_1^2)/(\xi_1^2 \xi^2)$, where $2\xi_0^{-2} = 73$ ⁸ ism supplemented by suitable boundary conditions at the interface $\mathcal{A}_{\alpha}+3\mathcal{B}_{\alpha}$, decouples equations as $\epsilon''_+=2\epsilon_\pm/\xi^2_+$. The letter defines $^{-74}$ 9 75 correlation lengths *ξ*[±] for ^a two-band system Choice $C_1 \tan \varphi_ = C_2 \tan \varphi_ + = 2(\xi_ -^2 - \xi_1^2)/(\xi_1^2 \xi_ -^2)$, where $2\xi_ \alpha^{-2} =$ \mathcal{A}_{α} + 3 \mathcal{B}_{α} , decouples equations as $\epsilon''_{\pm} = 2\epsilon_{\pm}/\xi_{\pm}^2$. The letter defines

two-band (
$$
\alpha = 1, 2
$$
) superconductor in zero magnetic field. By $2\xi_{\pm}^{-2} = \xi_1^{-2} + \xi_2^{-2} \pm \sqrt{(\xi_1^{-2} - \xi_2^{-2})^2 + C_1C_2}$. (6) 77
Exaking into account Josephson tunneling between bands the free-

 14 and 10λ , λ and λ a the units of *λ*.

16 82 densate is characterized by length scale *ξ*1*,*2, respectively. Inter- $\frac{17}{17}$ where expansion coefficients read as [27] $\frac{17}{17}$ band pairing mixes coherency channels so that superconductivity as ¹⁸ $a_n = W_0$ $a_n/det \hat{W} = 0$ $\ln [0.13\hbar \omega_D/(k_BT)]$ restoration in the joint condensate consists of two modes scaled as 19 $\frac{a}{b}$ 85 $\frac{b}{c}$ 85 $\frac{b}{c}$ 85 $\frac{b}{d}$ 85 $\frac{c}{d}$ $b_{\alpha} = 0.11 \rho_{\alpha}/(k_{\rm B}T)^2$, $K_{\alpha} = b_{\alpha} \hbar^2 v_{\rm F\alpha}^2/6$, (2) mensional correlation lengths *ξ*±λ dramatically: *ξ*−λ behaves crit- ₈₆ 21 87 ically diverging at the phase-transition point *^T*^c , while *ξ*+*λ* stays always finite [\[31,32\].](#page--1-0)

mensionless mass of the Leggett mode.

2.2. Asymptotic near boundary

29 α S α 1 $\frac{30}{30}$ $\frac{4\alpha v_{\alpha}}{30}$ binds $\frac{30}{30}$ binds $\frac{100}{30}$ and $\frac{100}{30}$ trivial value signaling time-reversal symmetry breaking [\[33\].](#page--1-0) In $\frac{96}{30}$ this case density and phase modes become mixed. Next we assume that interface suppresses superconductivity as for the border with magnetic material or normal metal, and neglect time-reversal symmetry breakdown taking ψ mod $\pi = 0$. Then the Ginzburg– Landau equations can be linearised as $\mathcal{A}_{\alpha} f_{\alpha} \mp \mathcal{C}_{\alpha} f_{3-\alpha} = f''_{\alpha}$, where modes

$$
f_1 = \cos \theta - f - \sin \theta + f_+ \tag{7}
$$

$$
f_2 = \sin \theta_- f_- + \cos \theta_+ f_+.
$$

By taking $C_1 \tan \theta_- = C_2 \tan \theta_+ = \pm 2(\Gamma_- - \Gamma_1)/(\Gamma_- \Gamma_1)$, where $\Gamma_{\alpha} = 2/\mathcal{A}_{\alpha}$, we obtain $f''_{\pm} = 2f_{\pm}/\Gamma_{\pm}$ with

⁴⁴ field [30].
For further analysis it is convenient to rescale quantities en-
⁴⁵
$$
2/\Gamma_{\pm} = 1/\Gamma_1 + 1/\Gamma_2 \pm \sqrt{(1/\Gamma_1 - 1/\Gamma_2)^2 + C_1C_2}.
$$
 (8)

Dimensionless length scales of the problem are given by $\gamma_{\pm} = \sqrt{|\Gamma_{\pm}|}$. The latter ones define the healing of two-band superconductivity close to its interface.

Dimensional lengths *γ*±*λ* have very unusual properties [\[34\]](#page--1-0) diverging respectively at the temperatures $T_{c\pm}$ given by

$$
\frac{52}{53} \quad \mathcal{A}_{\alpha} f_{\alpha} + G_{\alpha}^2 f_{\alpha} \psi'^2 - C_{\alpha} f_{3-\alpha} \cos \psi + \mathcal{B}_{\alpha} f_{\alpha}^3 = f_{\alpha}'' ,\n\qquad \qquad 2/\ln[1.13\hbar\omega_D/(k_B T_{\rm ct})] = \sigma \mp \sqrt{\sigma^2 - 4\rho_1 \rho_2 \det \hat{W}},\n\qquad (9) \quad \frac{118}{115}
$$

55 121 sponds to the critical temperature of the joint condensate and it is ^a point where *γ*−*λ* becomes infinitely large. Smaller temperature T_{c+} defines singularity of $\gamma_+ \lambda$. This point has physical meaning only for vanishing interband interaction when $T_{c\pm}$ approach critical temperatures for non-interacting condensates, $T_{c1,2}$, respectively.

⁶² by one divergent and one finite correlation length, coherency near ¹²⁸ ⁶³ 2.1. Asymptotic near bulk state the state of the state of the state of time-reversal-symmetry respecting surface is defined by two di-⁶⁴ 130 vergent length scales. Such a peculiarity is in strong contract to ¹³⁰ 65 Deviations $\epsilon_{\alpha} = 1 - f_{\alpha}$ from the bulk state determined by conventional model, where same length scale appears in both spa- 131 $f_{\alpha} = 1$ and $\psi = 0$ are characterized in the linear approximation tial domains. tial domains.

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