Journal of Alloys and Compounds, 195 (1993) 579–582
JALCOM 7532

WEAK LINK EFFECTS IN THE SURFACE IMPEDANCE OF CUPRATE SUPERCONDUCTORS

J. Halbritter
Kernforschungszentrum Karlsruhe, Institut für Materialforschung I,
Postfach 3640, 7500 Karlsruhe, Germany

ABSTRACT

The leading indicator for quality in rf superconductivity are: the weak link (WL) density and their quality which is given by critical current $j_{cJ}(T \approx 0, B \approx 0)$, Josephson penetration depth $\lambda_J \propto 1/\sqrt{j_{cJ}}$ and normal (leakage) tunnel current j_{bl}. The $j_{cJ}(T,B)$- and $j_{bl}(T)$-values explain penetretion depth λ_{res} and surface resistance $R_{res} = (\omega\mu_0)^2\lambda_J{}^3\, j_{bl}/2$ quantitatively and in temperature $\propto(a + T^n)$; $n \approx 1$, and $\propto(b + H^n)$; $n \approx 1$ $H > H_{c1J}$ in field dependence. Here H_{c1J} is the field where Josephson fluxons penetrate into WL's enhancing the penetration depth and thus the rf residual losses. For thinner films $t < \lambda_J$, R_{res} is enhanced further by λ_J/t and field dependencies are changed by enlarged penetration depths $\lambda^{\perp}{}_J = \lambda_J{}^2/2t$, by flux focusing and by demagnetization.

1. INTRODUCTION TO BULK WL SURFACE IMPEDANCE

Experimentally, cuprate superconductors show penetration depths $\lambda(T)$ and surface resistances $R(T)$, which because of their magnitude (10^1 - 10^6 above BCS [1,2]) and temperature and field dependencies ($\propto (T/T)^m$, $m \approx 1$, $T < T_c/2$)[2] well above expectations, have been related to extrinsic properties. In [2] evidence was presented that all "residual rf effects" in: magnitude-, frequency-, temperature-, dc resistance-, and field- dependence can be related to "weak links" (WL) Here WL stands for planar defects (Fig. 1) being weakly superconducting only, i. e., being crossed by a reduced Josephson current j_{cJ} where the reduction is compensated by a normal, leakage current j_{bl} The weak Josephson coupling yields a long Josephson penetration depth $\lambda_J > 1$ µm causing the destruction of rf shielding deep into the superconductor and dissipation described in a RSJ-model [3]. In lowest order approximation the intrinsic (I) and weak link (J) bulk impedances in series yield

$$\lambda_{eff} = (1 - \mu)\, \lambda_I + \mu\, \lambda_J \tag{1 1}$$

$$R_{eff} \simeq (1 - \mu)\, R_I + \mu\, R_J \quad \text{and}$$

with $\mu \simeq 2\, \lambda_I / a$ as areal ratio for $\lambda_I \ll a$ being the mean grain size [3]. The seize a is most easily obtained by scanning tunnel microscopy (STM) showing [4] for intragrain WL's a ~ 2 - 2 µm (epitaxial film), a ≥ 10 µm (single crystal) and for intergrain WL's a ~ 1 - 50 µm. The accepted properties for inter- and intragrain WL's are summarized in Table 1.

As discussed by the author [5], at the banks of the cuprate the energy gap of localized states $\Delta_s(x)$ is reduced and thus the supercurrent (j_{cJ}) is reduced, too, whereas a large normal (leakage) current (j_{bl}) is carried [6] via localized states with $\Delta_s = 0$ in the midth of the barrier . For intragrain planar defects, as e. g., small angle grain boundaries [3 - 6], the localized states may be caused by O-disorder in the chains, e. g., due to strain. As obvious by this sketch, the WL consists of nanoshorts (Ø ≈ 1 nm², $j_{cJ}(0) > 5 \cdot 10^7$A/cm²) in parallel and their density makes up the mean Josephson current $\overline{j_{cJ}(0)} \leq 10^4$ - 10^7 A/cm² [5, 6].

In [2] the physics of the rf residual surface impedance is worked out in detail. For example, it is shown that $j_{cJ} \propto 1/R_{bn}{}^2$ holds with R_{bn} (Ωcm²) as WL grain boundary resistance thus yielding as Josephson penetration depth

$$\lambda_J(T, H) \propto 1 \sqrt{j_{cJ}(T, H)} \propto R_{bn} \tag{1.2}$$

$$R_J(T, H) \simeq (\omega\, \mu_0)^2\, \lambda_J^3(T, H)\, a/2R_{bl} \propto R_{bn}^2 \tag{1.3}$$

and weak link surface resistance with R_{bl} (Ω cm²) the leakage current grain boundary resistance [2,3]. An exponential $\exp(-\Delta_s/kT)$

0925-8388/93/$06.00

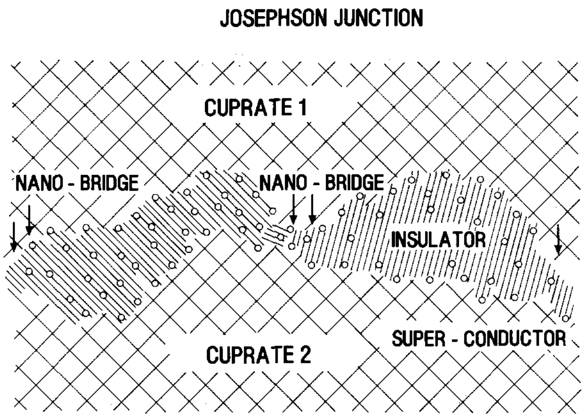

Fig. 1: Sketch of a small part of a planar intergrain (intra-) defect with localized states (o) in the insulator which mediate a tunnel current simulating nanoshorts [5, 6].

($\Delta_g/kT \leq 2$) or a linear T increase of $\lambda_J(T)$ and $R_J(T)$ can be related to the temperature dependencies of $R_{bl}(T)$ or $j_{cJ}(T)$. But the field dependence is more informative which is due to the small [2] $H_{c1J} \approx \lambda_I/\lambda_J\, H_{cI}$ where Josephson fluxons enter fast not hindered by a surface barrier. In rf fields the Josephson fluxon do not show flux flow or flux creep to speak off. Thus, e.g., the frequency, field or orientation dependence of the fluxon surface impedance is distinctively different to Abrikosov fluxons [2, 7]. Estimates for best films or crystals yield $\mu = 0.3$ as areal ratio for crystal (island) size of 1µm deduced from STM [4].Then for $\omega < \omega_J$ (Josephson plasma frequency)

$$R_{res}(0) \simeq 1.2 - 12\ \text{m}\Omega (f/0.1\text{THz})^2; \qquad (1.4)$$

is obtained as lower limit. To date, measured $R(T \leq 0.9T_c, \omega < \omega_J)$-values are larger than $R_I(T)$. Weak links seem to dominate with $R(T \leq 0.9T_c) \simeq R_{res} \propto \lambda_J{}^3(T)\lambda_I(T)/R_{bl}(T)$ as temperature dependence, and as field dependence H^2 up to H_{c1J} where a linear increase takes over [1,2].

2. THIN FILM SURFACE IMPEDANCE

The above equations hold for bulk cuprates, i. e., thickness $t \gg \lambda_I$ or λ_J. Most "good films" produced to date are with t~0.1 - 0.2 µm comparable or thinner than λ_I and λ_J. Neglecting transmission one obtains with the bulk impendance Z an effective impedance Z_{eff} given for $\lambda \gg t$ by the complex conductivities σ_I and σ_{Ji} of several types "i" of weak or strong links

$$Z_{eff} = Z \coth t/\lambda \approx 1/t \left\{ 1/\sigma_I + \sum 1/\sigma_J^i \right\} \qquad (2.1)$$

Below $0{,}9T_c$ the intrinsic losses can be neglected and for $\omega < \omega_J \approx 10$ THz [3]

$$R_{eff} \cdot t \simeq (\omega \mu_o)^2 \sum \frac{\lambda_J^4 \lambda_I^2 / a_i R_{bl}^i}{1 + (\omega \tau_i)^2} \qquad (2.2)$$

holds. Here, $\tau_i = \hbar/2ej^i_{cJ}R^i_{bl}$ describes the leakage current losses in a RSJ model [3].The reactance is given by

$$X_{eff}\, t \simeq \omega \mu o \lambda_I^2 (1 + \sum \frac{\lambda_J^2 / a_i \lambda_I}{1 + (\omega \tau_i)^2} \qquad (2.3)$$

Comparing these thin film results with Eq. (1.1) the WL enhancement λ_J/t is obvious. For rf current carrying thin strips [8] the thin film impendance is given by

$$Z_{eff}^{strip} = Z \coth t/2\lambda \qquad (2.4)$$

corresponding to a substitution of t ("one side") by t/2 ("two sides") in Eqs. (2.1) - (2.3). In endplate measurements in Eq. (2.1) the "transmission" has to be added being described best by the impedance Z_{sub} at the backside of the film

$$Z_{eff}^{end} = Z \frac{\coth t/\lambda + Z/Z_{sub}}{1 + Z/Z_{sub} \coth t/\lambda} \qquad (2.5)$$

For normal conducting YBCO films $t \ll \lambda$ holds and thus WL corrections of (2.5) are negligible. In the superconducting state $t \approx \lambda_I$ and $t \ll \lambda_J$ yield enhanced transmission via WL's proportional to $(\lambda_J/t)^2$. The interfering transmission components given by (2.5) with λ_I and λ_J make endplate measurements difficult to analyze in the superconducting state. At the end a third thin film impedance should be mentioned for the film perturbing a uniform H - rf field

$$Z_{eff}^{per} = Z \left(\tanh \frac{t}{2\lambda} + \frac{t}{2\lambda \cosh^2 t/2\lambda} \right) \qquad (2.6)$$

The latter impedance $Z_{eff}^{per} \approx Z \cdot t/\lambda$ ($t \ll \lambda$) is smaller than the bulk impedance Z whereas Z_{eff}^{end} and Z_{eff}^{strip} are larger than the bulk impedance. For thin films the response to magnetic fields is enhanced as compared to the bulk [1,2,7]. This is due to the reduced shielding of magnetic fields as described in Eq. (2.3). This lowers H_{c1J} [1], but also: field enhancements, flux focusing and demagnetization [9] have to be taken into account, aside of frozen-in flux. But like in the bulk, these effects can be described in the phase diagram depicted in Fig. 2.

3. COMPARISON WITH EXPERIMENTS AND DISCUSSION

In [1, 2] magnitude, frequency, temperature and observed field dependencies of Nb, NbN and YBCO surfaces have successfully described by WL's. Here, some new experiments are analyzed [7 - 15]. The temperature dependence of the WL model [2] has already successfully explained $\lambda(T)$ of epitaxial films [10] showing a small gap ($2\,\Delta/kT_c \leq 2$) below $T_c>/2$ and a large gap ($2\Delta/kT_c \approx 4.5$) above $T_c/2$. Recent deoxygenation and O-ordering experiments [11] show similar small gap values in R(T) below $T_c/2$ and smaller R_{res}-values for a higher O content or order. These observation are explained by WL's because O-loss and O-disorder reduces j_{cJ} and enhance j_{bl} of WL's [5]. In epitaxial films intragrain WL's change $\lambda(T)$ by about 10 % [10] in line with Eq. (2.3) and thus by deoxygenation WL's change $\lambda(T)$ by a similar amount. In this connection it should be mentioned that in endplate measurements [11] WL's simulate an enhanced geometry factor and λ (T) via Eq. (2.5). Despite the small λ_J-change [10] $j_{bl} \approx j_{bn} - j_{cJ}$ can grow drastically, where for large j_{cJ}-values, i.e. small j_{bl}- and R_{res}- values, $j_{cJ}(T) \propto j_{bl}(T)$ depends exponentially on T ($T<T_c/2$) with $2\Delta/kT_c \leq 2$ [5.6], as found for $R_{res}(T)$ in [11]. New infrared measurements [12] allowed a deduction of a_i and ι^i of Sect. 2: $a_1 = 1$ µm, $1/\iota_1 = 0.15$ THz and $a_2 = 3$µm, $1/\iota_2 = 4.8$ THz for $j_{cJ} \approx 10^6$ A/cm^2. These two types of WL fit nicely to Table 1 and to STM-measurements.

In discussing new Z(H)-results, we start with measurements in dc fields $H_{dc} \gg H_{rf}$ of bulk YBCO [7]. The $R(H_{dc})$ increase shows $R_{\parallel} > R_{\perp}$ and $R_J(H) \propto 1/(H+H^*_{C1J})$ with $H_{c1J}(0) \approx 100$ Oe. In this material intergrain weak links exist also with $H_{c1J} \approx 1$ Oe as inferred from ESR measurements [7] both in line with Table 1. The penetration of Abrikosov fluxons occurs at $H_{c1} \approx 0.1$ T. In contrast to melt -textured YBCO showing only some intergrain WL, sintered YBCO is dominated by intergrain WL with $H_{C1J} \approx 1$ Oe (Table 1), yielding large surface resistance and reactance increases [1, 2]. Proofs for the flow of Abrikosov fluxons like $H_{c2} \approx 100$ T or $R \propto \sqrt{\omega}$ are found at higher fields $H \approx H_{C2}$ [12]. $R(H_{dc}^{\perp}) > (H_{dc}^{\parallel})$ and indications of ideal surfaces, like, surface barrier or surface superconductivity have not yet been observed in surface impedance experiments. This lack of the surface barrier is in line with the weakened superconductivity at such $\hat{a}$-$\hat{b}$-surfaces [5]. In addition to dc fluxons, rf field fluxons are generated fast for $H_{rf} > H_{C1J}$ (Fig. 2). This is due to the facts that WL ending at a surface yield a field enhancement destroying any surface barrier and that small j_{cJ} and large leakage current of weak links ease fluxon nucleation ($>10^{-10}$ sec) [2]. The fluxons enter weak links and enhance $\lambda_J(H)$ as described in [2]. The rf field fluxons are piling up at the surface which results in $R(H_{rf}) > R(H_{dc})$.

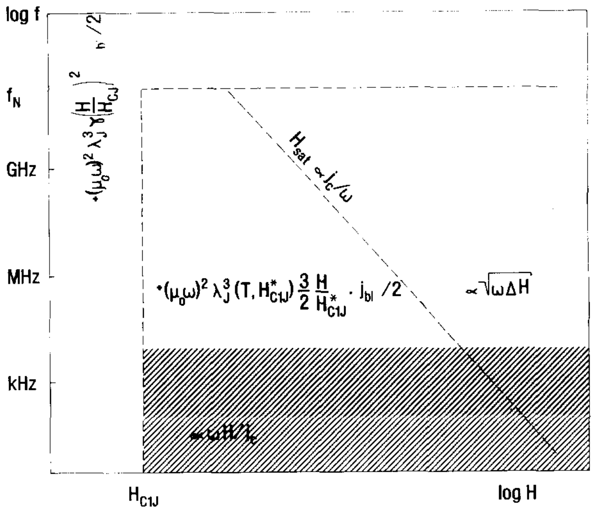

Fig. 2: Sketch of the different regimes of R_{res} (H_{rf}, ω) caused by fluxon penetration followed by flux creep and flux flow. Flux penetration occurs for frequencies below the fluxoid nucleation frequency f_n and for fields above H_{c1J}, H_{c1G}, or H_{c1I}. Below 10^4- 10^6 Hz the surface resistance is dominated by hysteresis losses. ($\propto \omega H$), with the further increasing frequency leakage current residual losses $\propto \omega^2 \lambda_J^3 j_{bl}$ take over. Below H_{C1} and above f_n no H_{rf} dependencies in R_{res} are encountered and one is observing R_{res} due to leakage currents and $H_{res} \approx 1 - 10^3$ Oe.

In contrast to the scarce experiments on high quality bulk YBCO, on epitaxial YBCO films more and more detailed experiments [8 - 15] are reported. Films with $t \approx 0.1 - 1$ µm are with $\lambda_I(T)$, $\lambda_J(T) \geq t$ in the thin film limit especially close to T_c, worked out in Sec. 2. As mentioned there, WL effects are enhanced by λ_J/t compared to the bulk. In addition, fields perpendicular to the film $H^{\perp}$ penetrate more easily because $H^{\perp}$ is enhanced by demagnetization and because $H^{\perp}c1$-fields are reduced by $\lambda^{\perp} > \lambda$. For dc-fields at $H_{C1G} \approx 100$ Oe R_J (H) increases and at $H_{C1I} \approx 700 - 1000$ Oe R_J (H) grows further by fluxon penetration into

Table 1: Parameters characterizing weak links and bulk, intrinsic YBCO at T = O assembled in [2] from experiments. The abbreviations "J" or "G" or "I" are subscripts added as needed for clarity. The critical currents $j_{cJ/G}$ cited are Josephson critical currents which together with pinning yield the actually measured critical current j_c. The fluxoids entering at H_{c1J} are Josephson fluxons for intergrain weak links turning to a more Abrikosov - like fluxon for the "G" - and "I" - system. Josephson fluxons move as linear array only which yields large activation energies U(T) proportional to the length of the weak links for fluxon motion.

Weak link	abbr.	R_{bn} Ωcm^2	j_c A/cm^2	λ_J μm	H_{c1} Oe	U eV
insulator		∞	0	∞	-	-
intergrain	J	$\leq 10^{-6}$	$\sim 10^2$	~ 30	≈ 1	1 - 10
intragrain	G	$\sim 5 \cdot 10^{-9}$	$\geq 10^4 - 10^7$	≈ 1	≈ 100	0.01 - 1
intrinsic	I	0	$\leq 4 \cdot 10^8$	0.14	≥ 1000	?

the bulk proportional to $R_{res} \propto \omega^2 H$. These proportionalities proof the dominance of WL losses and rule out flux flow type loss mechanism with $\propto \sqrt{\omega H}$. In rf fields, in addition to a small $H_{C1J} \approx 1$ Oe, dependencies proportional to H_{RF}^2 are found between 20 and 100 Oe. The detailed analysis yields [1,2,8]

$H(O)_{cJ} \simeq 0.1$ Tesla, $a \approx 1/8$ and $\gamma \simeq 2$.

By using an areal ratio $\mu \simeq 0.1$ (Eq. (1.1)) H_{cJ} reduces to 300 Oe, which fits nicely to the observed intragrain WL with $H_{c1G}(0) \approx 100$ Oe, like the a- and γ-values. With further increasing rf field a stronger R(H)- grows is observed hinting to heating or flux penetration $\propto 1/(H_{rf} + H_{C1G})$.

4. CONCLUSION

With the inter- and intragrain WL properties summarized in Table 1, the rf residual losses and residual penetration depth are explained in magnitude [1, 2]. In addition, T-[10,11], ω-[12], and H-dependencies [7-9,13 - 15] of Z proove the existence of the two types of WL's classified in Table 1 and yield an estimate of their density. Again, this confirms the observed rf residual surface impedances quantitatively and shows that WL's have to be reduced further to obtain superior material.

References

1. J. Halbritter, J. Appl. Phys. 68, 6315 (1990) and 71, 339 (1992)

2a. J. Halbritter, Proc. 5. Superconduction rf Workshop, Hamburg, 1991, (D. Proch Ed., DESY, HAMBURG, 1992), p. 939

2b. J. Halbritter, J. Superconductivity 5, 339 (1992) and MRS. Proc 275 (1992)

3. Todd Hylton, thesis (Stanford University, 1991)

4. e.g., Ultramicroscopy 42 - 44, 705 - 738 (1992)

5. J. Halbritter, Phys. Rev. B 46, Dec. (1992)

6. D. Dimos et al., Phys. Rev. B 41, 4038 (1990); P. Chaudhari et al., submitted

7. J. Wosik et al., MRS-Proc.275, 895 (1992) and IEEE Trans MAG 29 (1993)

8. D.E. Oates, et al., J. Superconducivity 5 (1992) and IEEE Trans MAG 29 (1993)

9. P.A. Rosenthal et al., Appl. Phys. Lett. 59, 3482 (1992)

10. St. Anlage et al., Phys. Rev. B 44, 9764 (1991)

11. N. Klein et al., IEEE Trans MAG-29, (1993); S. Orbach et al., this conference

12. J. Schützmann, thesis (University Regensburg, 1992)

13. J.Owliaei, Phys. Rev. Lett. submitted

14. J. Steinbeck et al., Appl. Superc. Conf., Chicago, August 1992

15. M.S. Pambiandri et al., IEEE Trans MAG 29 (1993)