ELSEVIER

Materials Chemistry and Physics 48 (1997) 94–99

MATERIALS CHEMISTRY AND PHYSICS

Resistive response to a microwave field in high temperature superconducting crystals

C.J. Wu, T.Y. Tseng

Department of Electronics Engineering and Institute of Electronics, National Chiao Tung University, Hsinchu, Taiwan, ROC

Received 7 February 1996; revised 3 May 1996

Abstract

The microwave properties of high temperature superconducting crystals in the resistive states are theoretically investigated. The single crystals in the shapes of platelet and cylinder in parallel field configuration are considered. The microwave responses are analyzed from the associated effective r.f. magnetic permeabilities. The influence of the anisotropic resistivity on the microwave response is stressed in an anisotropic superconductor. The results indicate the importance of thin edges of the platelet crystal to the microwave properties. In the isotropic superconductor, a relationship between the responses of a square rod and a cylinder is found. The results show that the microwave properties of a cylinder can be essentially replaced by those of a square rod and vice versa. Also the geometric effect on the response is illustrated in the isotropic superconductor.

Keywords: Anisotropic superconductor; Normal-state response; R.f. permeability; Microwave

1. Introduction

The microwave measurements provide some fundamental and practical information about the superconductors. The physics of superconducting state as well as the quasiparticle excitation can be extracted through the measurement of complex surface impedance, $Z_s = R_s + jX_s$, where R_s is the surface resistance and X_s the surface reactance. According to well-known two-fluid theory [1], R_s is closely related to the thermally excited quasiparticles, whereas X_s is related to the penetration depth $\lambda(T)$. In practical applications, the surface impedance also predominantly determines the performances of superconducting devices [2–4].

In microwave measurements of high temperature superconducting single-crystal platelets, two configurations are usually considered [5–9]. One is the perpendicular configuration in which the microwave magnetic field is perpendicularly applied to the main flat surfaces, namely, parallel to *c*-axis. In this configuration, the electrodynamics of a superconductor are less anisotropic and usually treated as isotropic for convenience. However, it involves a large demagnetizing field and is hard to deal with analytically. The other one is the parallel field configuration where the field is parallel to the *ab*-plane. The electromagnetic properties are thus anisotropic, especially in the Bi:2212 system. As reported in the literature, the normal-state anisotropic resistivity ratio ρ_c/ρ_{ab}, is about 10^5 for this system [10,11]. The field penetration depth through thin edges is then 300 times larger than that of main surfaces. Also, in mixed state the broadening of resistive transition below T_c is strongly anisotropic [8]. The effects of thin edges on microwave losses are therefore should be possibly taken into account.

Although the surface impedance is widely used to study the microwave properties of superconductors, it is not easy to calculate theoretically for a superconducting rectangular rod or cylinder. Another relevant quantity applied in microwave analysis is the effective dimensionless a.c. magnetic permeability, $\mu = \mu' - j\mu''$, which usually contains the information about the intrinsic features of superconductors together with the extrinsic ones, the sample dimension and geometry [12–16]. Recently, Gough and Exon [9] considered the normal-state microwave response in an anisotropic high-T_c superconducting crystal platelet in the parallel magnetic field. They derived the a.c. permeability from the assumption that superconductor is regarded as a linear system. The linear a.c. response is obtained from the integration of the impulse response. The impulse response, however, is obtained from the derivative of the unit step response. This is a familiar theorem commonly used in the linear system. Based on this calculated permeability, the authors pointed out the importance of the thin edges of a platelet on the microwave properties of anisotropic superconductors.

PII S0254-0584(96)01859-7

The purpose of this paper is to give a comparative study in normal-state response. We present a new expression for the permeability for an anisotropic rectangular rod. The influence of thin edges on microwave absorption is discussed for both anisotropic and isotropic superconductors. Special consideration of an isotropic square rod and cylinder reveals an interchangeable relationship of responses between these two geometries. By making use of the measured data in anisotropic resistivities for the extremely anisotropic high-T_c system Bi:2212, our theoretical results in permeability are essentially in accord with the experimental report on surface impedance. Based on the a.c. permeability given in this work for the anisotropic superconductor, we will also briefly discuss the generalization of the simple picture proposed by Geshkenbein [17] in interpreting the irreversibility line in mixed state.

2. Calculation of dimensionless a.c. permeability

Consider a resistive platelet with length $2b$, width $2a$, thickness $2c$ oriented in parallel field, as depicted in Fig. 1, which also shows the cross-section of platelet. We assume that the length is much larger than the thickness. This assumption permits us to ignore the demagnetizing field. The electrodynamics of the resistive sample is described by anisotropic magnetic flux diffusion equation:

$$\left(\rho_c\frac{\partial^2}{\partial x^2}+\rho_a\frac{\partial^2}{\partial y^2}\right)h=\mu_0\frac{\partial h}{\partial t} \tag{1}$$

where ρ_c and ρ_a are the resistivities along the c-axis and in the ab-plane (the ab-plane is assumed to be nearly isotropic). Eq. (1) is easily derived from Maxwell's equations. By letting, $x'=(\rho_a/\rho_c)^{1/4}x$, $y'=(\rho_c/\rho_a)^{1/4}y$ and $\sigma^{-1}=\rho_{\rm eff}=(\rho_c\rho_a)^{1/2}$ in addition to $h=h(x,y)\exp(j\omega t)$, Eq. (1) reduces to

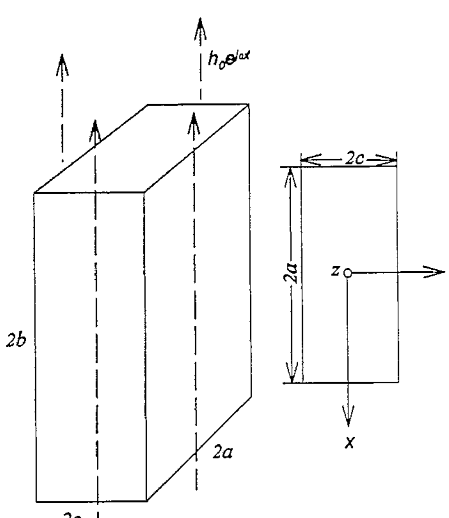

Fig. 1. The single-crystal platelet in the parallel field configuration where the microwave field is applied parallel to four planes of the platelet. The right shows the cross section of the platelet crystal where the x–z plane corresponds to the Cu–O ab-plane and the y-direction to the crystallographic c-axis.

$$\left(\frac{\partial^2}{\partial x'^2}+\frac{\partial^2}{\partial y'^2}-k^2\right)h(x',y')=0 \tag{2}$$

where $k^2=j\omega\mu_0\sigma$. The above equation, subject to the continuity boundary conditions for magnetic field at $x'=\pm(\rho_a/\rho_c)^{1/4}a$ and $y'=\pm(\rho_c/\rho_a)^{1/4}c$, describes a well-known electrodynamic problem. The exact solution for Eq. (1) is thus given by

$$h(x,y,t)=\sum_{n=0}^{\infty}(-1)^n\frac{2h_0}{q_n}\left[\cos\left(\frac{q_n}{a}x\right)\frac{\cosh(k_yy)}{\cosh(k_yc)}+\cos\left(\frac{q_n}{c}y\right)\frac{\cosh(k_xx)}{\cosh(k_xa)}\right]\exp(j\omega t) \tag{3}$$

where

$$k_x^2=\left(\frac{\rho_a}{\rho_c}\right)^{1/2}\left(\frac{q_n^2}{c^2(\rho_c/\rho_a)^{1/2}}+k^2\right)$$

$$k_y^2=\left(\frac{\rho_c}{\rho_a}\right)^{1/2}\left(\frac{q_n^2}{a^2(\rho_a/\rho_c)^{1/2}}+k^2\right)$$

$q_n=(n+1/2)\pi$, $n=0, 1, 2, 3, \ldots$ and h_0 is the amplitude of perturbed microwave magnetic field. The complex power per unit length in z-direction is readily calculated from the Poynting theorem, namely

$$\begin{aligned}P_{\rm av}&=\frac{1}{2}h_0\exp(-j\omega t)\oint_c E\,dl\\&=\frac{1}{2}j\omega\mu_0h_0\exp(-j\omega t)\int_{-c}^{c}\int_{-a}^{a}h(x,y,t)\,dx\,dy\\&=\frac{j\omega_0h_0^2(2a)(2c)}{2}\sum_{n=0}^{\infty}\frac{2}{(n+1/2)^2\pi^2}\\&\quad\times\left(\frac{\tanh(k_xa)}{k_xa}+\frac{\tanh(k_yc)}{k_yc}\right)\end{aligned} \tag{4}$$

The prefactor $j\omega\mu_0h_0^2(2a)(2c)/2$ is the (reactive) power flowing into the equivalent volume of free space per unit length. This can be well understood by considering the crystal as an isotropic insulator. In this limit, the summation in Eq. (4) converges to unify for a finite ratio a/c. The effective a.c. magnetic permeability for an anisotropic rectangular rod is thus defined as

$$\begin{aligned}\mu&=\mu'-j\mu''\\&=\sum_{n=0}^{\infty}\frac{2}{(n+1/2)^2\pi^2}\left(\frac{\tanh(k_xa)}{k_xa}+\frac{\tanh(k_yc)}{k_yc}\right)\end{aligned} \tag{5}$$

The imaginary part, μ'', indicates microwave loss and determines performance of superconducting device. The real part μ', however, is closely related to the resonance frequency when the sample is used as a part of resonant circuit. In order to numerically investigate the behavior of μ, it is convenient to express k_x and k_y in terms of anisotropic skin depths $\delta_a^2 = 2\rho_c/\mu_0\omega$ and $\delta_c^2 = 2\rho_a/\mu_0\omega$, the results are

$$k_x = \left(\frac{\rho_a}{\rho_c}\right)^{1/2}\left(\frac{(n+1/2)^2\pi^2}{c^2} + j2\delta_c^{-2}\right)^{1/2}$$

and

$$k_y = \left(\frac{\rho_c}{\rho_a}\right)^{1/2}\left(\frac{(n+1/2)^2\pi^2}{a^2} + j2\delta_a^{-2}\right)^{1/2}$$

The permeability in Eq. (5) obviously incorporates the material anisotropy and sample dimensions. It describes the microwave response of superconductor not only in the normal-state but also in mixed state, especially in the regime of thermally assisted flux flow (TAFF). In TAFF, the basic assumption is the existence of a linear resistivity, i.e. Ohm's law. Based on this idea, Kes et al. [16] and Geshkenbein et al. [17] have separately calculated the permeability for an *isotropic* slab. In fact, we have generalized the simple picture proposed by Geshkenbein et al. [17] to more general consideration because the permeability in Eq. (5) obviously incorporates all possible features due to anisotropy. The detailed description will be given in the part III later.

In addition, the derivation here appears to be easier and more direct than that given by Gough et al. [9]. The method described in their work is, in reality, not suitable for both anisotropic and isotropic cylinders because of the complication of the diffusion equation in cylindrical coordinates. A careful consideration reveals that the exact solution for an anisotropic cylinder is not possible. Nevertheless, the permeability for an anisotropic cylinder is easy to obtain. In an isotropic cylinder, Eq. (2) can be transformed, in terms of cylindrical coordinates, as

$$\left(\frac{d^2}{dr^2} + \frac{1}{r}\frac{d}{dr} - k^2\right)h(r) = 0 \tag{6}$$

The exact solution for $h(r)$ can be obtained with the aid of the boundary condition at $r=\rho$ (the radius of cylinder), with the result

$$h(r) = h_0\frac{I_0(r/\tilde{\lambda})}{I_0(\rho/\tilde{\lambda})} \tag{7}$$

where I_0 is the modified Bessel function of first kind with order zero, $\tilde{\lambda} = k^{-1} = \delta/(1+j)$ is the complex penetration length, and $\delta = (2/\omega\mu_0\sigma)^{1/2}$ is the skin depth of an isotropic cylinder with conductivity σ. The complex power P_{av} (per unit length) flowing into the isotropic cylinder is thus given by

$$P_{av} = \frac{j\omega\mu_0 h_0^2(\pi\rho^2)}{2}\,\frac{2\tilde{\lambda}}{\rho}\,\frac{I_1(\rho/\tilde{\lambda})}{I_0(\rho/\tilde{\lambda})} \tag{8}$$

where I_1 is the modified Bessel function of first kind with order one. Again the prefactor $j\omega\mu_0 h_0^2(\pi\rho^2)/2$ represents the power flowing into the equivalent free-space volume per unit length. Accordingly, the associated complex a.c. permeability for cylinder is

$$\mu_{\text{cyln}} = \frac{2\tilde{\lambda}}{\rho}\,\frac{I_1(\rho/\tilde{\lambda})}{I_0(\rho/\tilde{\lambda})} \tag{9}$$

The complex a.c. permeability is experimentally measurable in the microwave cavity perturbation method [9] and is commonly used in the analysis of microwave and a.c. properties of superconductors not only experimentally but theoretically. In this work, we shall try to investigate the relationship between the permeabilities of an isotropic cylinder and a square rod.

3. Results and discussion

The permeability of anisotropic square rod, Eq. (5), can be expressed as

$$\mu(X,Y) = \sum_{n=0}^{\infty}\frac{2}{q_n^2}\left(\frac{\tanh(q_n^2X^2/Y^2 + jX^2/2)^{1/2}}{(q_n^2X^2/Y^2 + jX^2/2)^{1/2}} + \frac{\tanh(q_n^2Y^2/X^2 + jY^2/2)^{1/2}}{(q_n^2Y^2/X^2 + jY^2/2)^{1/2}}\right) \tag{10}$$

where $X = 2c/\delta_c$ and $Y = 2a/\delta_a$ rely on frequency and temperature implicitly. The overall behavior of the imaginary part of $\mu(X,Y)$ is displayed in Fig. 2 where the surface plot is given as functions of X and Y. As can be seen in this figure, a minimum loss peak (0.366) occurs at $X=Y$, namely, $2c/\delta_c = 2a/\delta_a$ (see also in Fig. 3 for better observation). This is referred as an equivalent square rod. Other than that, the

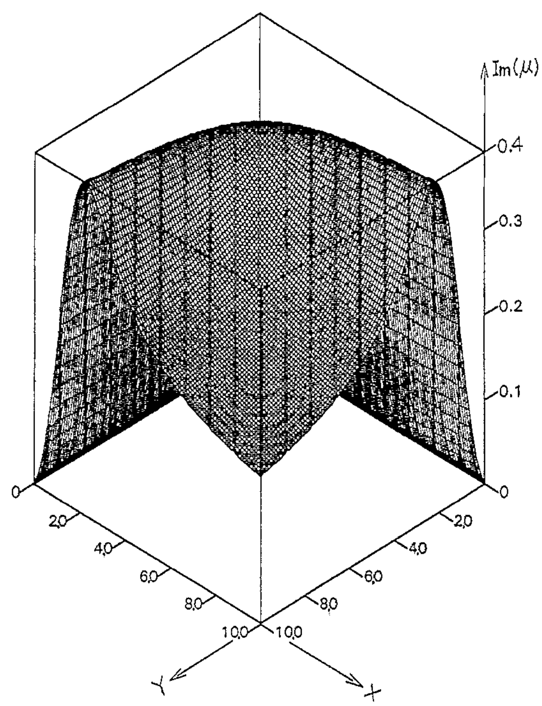

Fig. 2. The surface plot of imaginary part of permeability as functions of X and Y for an anisotropic rectangular platelet in Eq. (10). The X and Y are both taken from 0 to 10 for illustrative purpose.

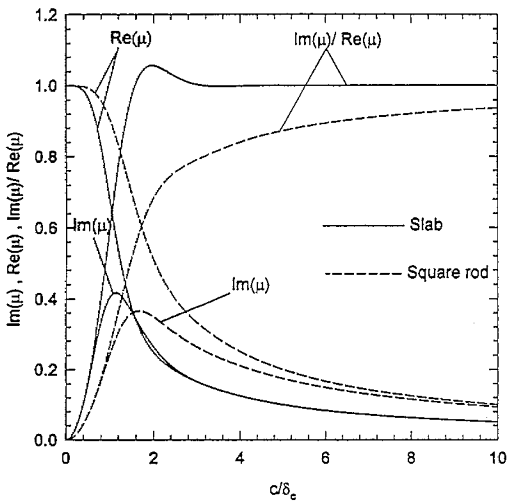

Fig. 3. The imaginary and real parts of permeabilities as a function of c/δ_c for both an anisotropic slab and a square rod. The peak value in μ'' is 0.417 for a slab, whereas it is 0.366 for a square rod. The variation is about 13% for the maximum peak of a slab.

peak value in μ'' will be greater than 0.366. Specifically, in the slab limit (defined as $a \to \infty$ and thickness $2c$), the permeability becomes

$$\mu_{\text{slab}} = \mu' - j\mu'' = \frac{\tanh((1+j)c/\delta_c)}{(1+j)c/\delta_c} \tag{11}$$

which attains a maximum loss peak (0.417) in μ'' as shown in Fig. 3 where comparison with an equivalent square rod is made. The microwave absorption in a slab is mainly due to the main flat surfaces, that is, the absorption due to thin edges is ignored. Meanwhile the μ''-peak occurs at $c \approx 1.127\delta_c$ (refer to Fig. 3), correspondingly, peak frequency is proportional to a-axis resistivity, a consequence of anisotropy. This feature is also shown in the static Meissner response based on the two-fluid model [18]. With the fact that the normal-state resistivities for high-T_c cuprates are linearly dependent on temperature, the frequency of μ'' peak in slab is thus also linear with temperature. We can easily verify this by calculation of μ'' from Eq. (11). Simple manipulation yields

$$\mu'' = \frac{1}{X}\frac{\sinh X - \sin X}{\cosh X + \cos X} \tag{12}$$

which reaches a maximum when $X = 2.254$. The nature of the loss peak is usually argued as the skin size effect [17]. Based on the above results, we conclude that the inclusion of microwave absorption from the thin edges has effectively decreased the loss peak. In other words, the effect of considering microwave losses from all four planes parallel to the field is always to reduce the peak in microwave loss relative to that calculated across two main parallel faces alone. Thus it can be roughly argued that the field penetration through thin edges decreases the gradient of magnetic flux density originally penetrating through main surface, which in turn will lower the current density flowing in the cross-section according to Ampere's law. The microwave absorption is consequently decreased markedly. The results illustrate the importance of thin edges on microwave losses. Care should therefore be taken when considering the single-crystal platelet in microwave applications. By the way, the permeability of a slab in Eq. (11) derived from Eq. (5) (by letting $a \to \infty$) was also treated by Gough et al. [9]. They considered a slab limit from the assumption of $\rho_c = 0$, i.e. the penetration depth through thin edge (along a-direction) is zero. However, it is a quite non-physical assumption and solely mathematical treatment, because the conductivity of a high temperature superconductor in the normal-state is by no means zero. Therefore in order to reduce to the permeability of a slab from Eq. (5), one must use $a \to \infty$ instead of $\rho_c = 0$.

In Fig. 4, we plot the imaginary and real parts of permeability in Eq. (5) as a function of temperature for an extremely anisotropic high-T_c superconductor system, Bi:2212 [19]. The normal-state resistivities are $\rho_a \approx 4.6 \times 10^{-7} T$ (Ω cm) and $\rho_c \approx \rho_a(5 + (3/0.46) \times 10^4 T^{-2}) \times 10^4$ (Ω cm) [10]. The thickness and width are taken to be, $2a = 1.5$ mm and $2c = 10$ μm, respectively. The figure shows some good consistency with the measured microwave surface impedance reported by Exon et al. [19]. It indicates the validity of our derivation based on anisotropic resistive model. Also, the anisotropic resistivity ratio permits us to determine aspect ratio, a/c, for obtaining the minimum loss peak. The range is found to be 228–386 for Bi:2212 system. One can thus design a platelet with suitable dimensions which has a minimum loss peak in the temperature range of interest.

We next examine the geometric effect on microwave response in the isotropic superconductors. For an isotropic rectangular rod ($\rho_c = \rho_a$), the minimum loss peak (0.366) also occurs at the *real* square rod in shape ($a = c$). The maximum loss peak (0.417) remains for a slab. As described previously, for strongly anisotropic superconductor, Bi:2212,

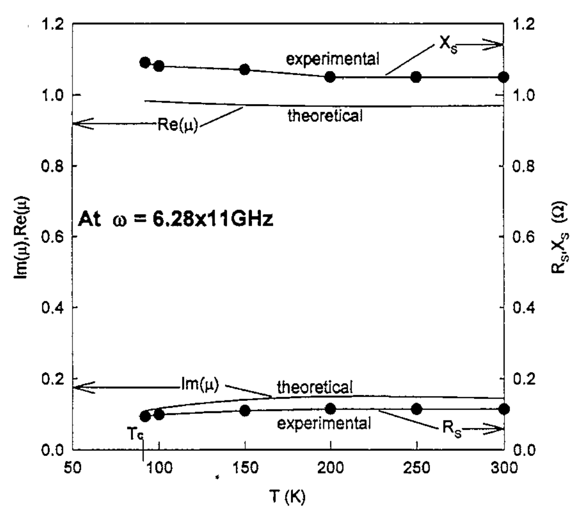

Fig. 4. The temperature-dependent imaginary and real parts of the permeability of an anisotropic platelet in Eq. (5). The surface resistance and reactance are taken from Ref. [19]. The material parameters and dimensions are given in the text. Good consistency between theoretical and experimental results is observed.

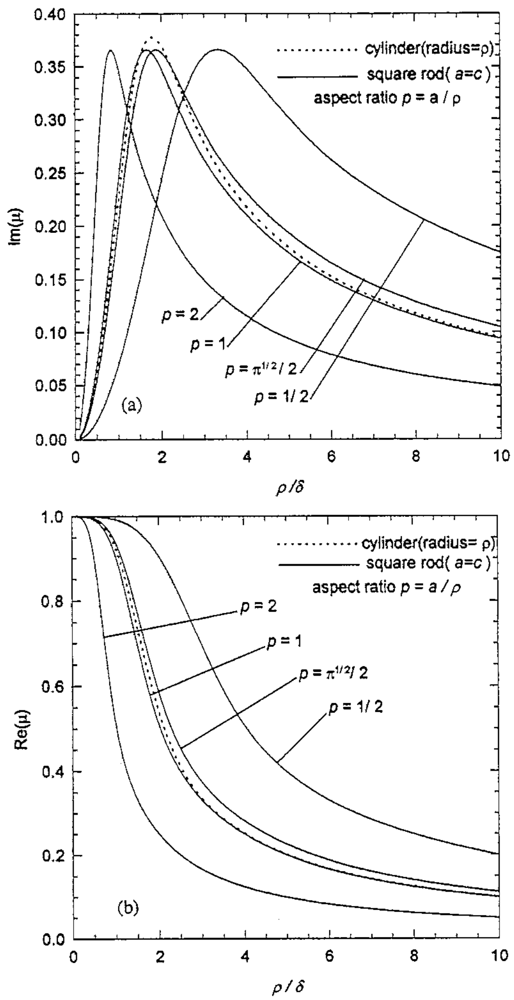

Fig. 5. (a) The imaginary parts of the permeabilities for an isotropic cylinder in Eq. (9) and a square rod in Eq. (10) at various aspect ratios p. The aspect ratio is defined in the figure. (b) The real parts of the permeabilities for an isotropic cylinder in Eq. (9) and a square rod in Eq. (10) at various aspect ratios p.

the minimum μ'' peak occurs at the equivalent square rod, namely $c/a=\delta_c/\delta_a=(\rho_a/\rho_c)^{1/2}\approx 1/300$. For a sample with typical width $2a=1$ mm, one has thickness $2c\approx 3$ μm, corresponding to a thin platelet. However, in order to obtain the minimum μ'' peak in an *isotropic* platelet, the thickness should be taken to be as large as the width (namely, the thick platelet). If one still takes, say, $2a=1$ mm and $2c\approx 3$ μm in the isotropic one, one finds that the peak height in μ'' is very close to that for the slab which in turn means the effects of thin edges are obscure. Relatively speaking, it indicates that the effect of *thin* edges on the μ'' peak in an isotropic platelet is not as significant as for an anisotropic platelet. Nevertheless, they actually do influence the microwave properties appreciably. This point was ignored in the work of Gough et al. [9]. Fig. 5(a) and (b) demonstrate the imaginary and real parts of permeabilities for both cylinder in Eq. (9), and square rod ($a=c$ and $\delta_c=\delta_a\equiv\delta$) in Eq. (5) or (10), respectively. We have used the aspect ratio, p, defined as the ratio of the half-width to the radius of the cylinder, i.e. $p=a/\rho$. As can be seen, the overall permeability of a cylinder essentially coincides with that of a square rod when $p=1$. Equivalently this means that the cross-sectional area ratio of a cylinder to a square rod is $\pi/4\approx 0.785$ instead of unity by intuition. The only small discrepancy between the two geometries is the peak value in μ''. Fig. 5(a) shows that the loss peak in the cylinder is slightly greater than that in the square rod. Other than that, the microwave permeability of a cylinder can be approximately replaced by that of a square rod and vice versa provided that aspect ratio, p, is taken to be about one. We can further verify this by considering the limits of the radius and the side length being much larger than the skin depth. For $a/\delta\gg 1$ (in square rod), the permeability for an isotropic square rod can be simplified, from Eq. (10), as

$$\mu_{\text{square}}\approx\frac{\delta}{a}(1-\mathrm{j}) \tag{13}$$

where the identity

$$\sum_{\text{odd}}\frac{1}{n^2}=\frac{\pi^2}{8}$$

has been used to simplify this result. The power absorption in Eq. (4) leads to

$$P_{\text{av}}=\frac{\mathrm{j}\omega\mu_0 h_0^2}{4}\times 8a\delta(1-\mathrm{j}) \tag{14}$$

Similarly, in the limit of $\rho/\delta\gg 1$ for cylinder. The permeability in Eq. (9) becomes

$$\mu_{\text{cyln}}\approx\frac{2\tilde{\lambda}}{\rho}=\frac{\delta}{\rho}(1-\mathrm{j}) \tag{15}$$

Accordingly, the power absorption described in Eq. (8) is given by

$$P_{\text{av}}=\frac{\mathrm{j}\omega\mu_0 h_0^2}{4}\times 2\pi p\delta(1-\mathrm{j}) \tag{16}$$

Based on Eqs. (13) and (15), to make $\mu_{\text{square}}=\mu_{\text{cyln}}$, one would find that $a=\rho$, namely the aspect ratio $p=1$. The previous argument from numerical results shown in Fig. 5 is thus evidently confirmed. Another feature is of note, i.e. from Eqs. (14) and (16) the total microwave power loss per unit length is proportional to the product of the circumference and the skin depth for both the square rod and cylinder in these limits.

The a.c. absorption for high temperature superconductors in the mixed state was previously discussed within the framework of TAFF by Geshkenbein et al. [17]. According to the idea of TAFF, the authors simply treated the isotropic superconducting slab as a normal conductor and proposed a simple picture to argue that the transition in μ' and the peak in μ'' are due to the skin size effect, namely the skin depth is of the order of the size of sample. The frequency at the peak, ω_p is proportional to the static resistivity in half-thickness of the slab. Also, the position of μ'' peak determines the onset of the irreversibility of superconductors in the mixed state [20].

Based on these facts and with the aid of our derivation in Eq. (5) together with the results in Figs. 2 and 3, one would conclude that the irreversibility line should closely rely on the size and geometry of the sample. In addition, the irreversibility line is frequency dependent because the onset of the irreversibility line is shifted to higher frequency in the square rod. This frequency dependence was previously observed experimentally [21]. In other words, the onset of irreversible behavior in the *H–T* diagram connects with the field orientation and the sample dimension as well. To sum up, our general consideration here has explicitly extended the physical picture proposed by Geshkenbein et al. [17,22].

4. Conclusion

The microwave properties of a normal-state superconducting single-crystal platelet have been examined based on the dimensionless a.c. permeability calculated from the solution of anisotropic diffusion equation. The role of thin edges in microwave response is clearly illustrated. The microwave dissipation peak is depressed due to the inclusion of field penetration through thin edges of platelet and has a minimum loss peak in the shape of square rod. In the extreme case, the slab, a maximum loss peak is attained. By feeding the measured resistivities into the permeability, one finds a good accordance with the measured surface impedance. In the isotropic superconductor, we also illustrate the influence of thin edges on microwave response. A special examination on permeabilities of the isotropic cylinder and square rod reveals an interesting relationship of their responses, namely that the responses of these two geometries can be essentially interchanged if necessary. Our derivation presented here can also be applied to relate the irreversibility line in the mixed state with the sample dimensions as well as the material anisotropy.

Acknowledgements

This work is supported by the National Science Council of ROC under project No. NSC84-2112-M009-026.

References

[1] T. Van Duzer and C.W. Turner, *Principles of Superconductive Devices and Circuits*, Elsevier, New York, 1981.
[2] H. How, G. Seed, C. Vittoria, D.B. Chrisey, J.S. Horwitz, C. Carosella and V. Folen, *IEEE Trans. MTT, 40* (1992) 1668.
[3] C. Wilker, Z.Y. Shen, P. Pang, D.W. Face, W.L. Holstein, A.L. Matthews and D.B. Laubacher, *IEEE Trans. MTT, 39* (1991) 1462.
[4] S.H. Talisa, M.A. Janocko, C. Moskowitz, J. Talvacchio, J.F. Billing, R. Brown, D.C. Buck, C.K. Jones, B.R. Mcavoy, G.R. Wanger and D.H. Watt, *IEEE Trans. MTT, 39* (1991) 448.
[5] D.-H. Wu and S. Sridhar, *Phys. Rev. Lett., 65* (1990) 2074.
[6] T. Hanaguri, Y. Iino, A. Maeda, Naobumi and K. Kishio, *Physica C, 235–240* (1994) 1991.
[7] T.T.M. Palstra, B. Batlogg, L.F. Schneemeyer and J.V. Waszczak, *Phys. Rev. B, 43* (1991) 3756.
[8] T.T.M. Palstra, B. Batlogg, R.B. van Dover, L.F. Schneemeyer and J.V. Waszczak, *Phys. Rev. B, 41* (1991) 6621.
[9] C.E. Gough and N.J. Exon, *Phys. Rev. B, 50* (1994) 488.
[10] S. Martin, A.T. Fiory, R.M. Fleming, L.F. Schneemeyer and J.V. Waszczak, *Phys. Rev. Lett., 60* (1988) 2194.
[11] R. Busch, G. Ries, H. Werthner, G. Kreiselmeyer and G. Saemann-Ischenko, *Phys. Rev. Lett., 69* (1992) 522.
[12] J.R. Clem, H.R. Kerchner and S.T. Sekula, *Phys. Rev. B, 14* (1976) 1893.
[13] M.W. Coffey and J.R. Clem, *Phys. Rev. B, 45* (1992) 10527.
[14] M.W. Coffey and J.R. Clem, *Phys. Rev. B, 45* (1992) 9872.
[15] Ph. Seng, R. Gross, U. Baier, M. Rupp, D. Koelle, R.P. Huebener, P. Schmitt, G. Saemann-Ischenko and L. Schultz, *Physica C, 19* (1992) 403.
[16] P.H. Kes, J. Aarts, J. van den Berg, C.J. van der Beek and J.A. Mydosh, *Supercond. Sci. Technol., 1* (1989) 242.
[17] V.B. Geshkenbein, V.M. Vinokur and R. Fehrenbacher, *Phys. Rev., B43* (1991) 3748.
[18] T.P. Orlando, K.A. Derlin, *Foundations of Applied Superconductivity*, Addison-Wesley, Reading, MA, 1991.
[19] N. Exon, M. Lancaster, A. Porch, G. Yang, C.E. Gough, *IEEE Trans. Appl. Supercond., 3* (1993) 1442.
[20] C.J. van der Beek and P.H. Kes, *Phys. Rev. B, 43* (1991) 13032.
[21] A.P. Malozemoff, T.K. Worthngton, Y. Yeshurun, F. Holtzberg and P.H. Kes, *Phys. Rev. B, 38* (1988) 7203.
[22] C.J. Wu and T.Y. Tseng, *Physica C, 259* (1996) 61.