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Non–linear microwave surface impedance of patterned $YBa_2Cu_3O_7$ thin films

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Abstract

We have patterned thin film $YBa_2Cu_3O_{7-\delta}$ (YBCO) coplanar resonators to characterise the surface impedance of our films[1]. Our best film, with growth conditions optimised for good dc transport properties, yields a resonator with an unloaded quality factor in excess of 40000 at 15K and 8GHz, with a corresponding surface resistance around $25\mu\Omega$. The impedance is constant for microwave fields $H_{\rm rf}$ up to 10^4Am^{-1}, above which it increases rapidly. This contrasts with the case of less well optimised films; although the surface resistances of these films may be less than a factor of 2 larger than those for optimised films, the non–linear effects are much more pronounced and occur at much lower microwave fields, and they are therefore less suitable for high field applications.

1. Introduction

Coplanar resonators are ideally suited to the study of non–linear effects in patterned high–T_c thin films. Only one film surface is required for fabrication, thus removing the need for double–sided depositions. The microwave current density at the edges of the central strip is large, particularly if the spacing between the strip and the ground planes is smaller than the strip width (see figure 1). The performance of the resonators is therefore governed by the film quality at the patterned edges.

For c–axis oriented films the microwave currents flow only along the ab–planes and modelling of the current distribution in the resonator allows us to calculate the ab–plane surface impedance $Z_S = R_S + iX_S$, where $X_S = \omega\mu_0\lambda$ and λ is the ab–plane magnetic penetration depth. We can vary the edge microwave field $H_{\rm rf}$ over four orders of magnitude between around 1Am^{-1} and 50000Am^{-1} with the aid of a microwave amplifier. In this paper we present Z_S measurements of our patterned films over this full range of $H_{\rm rf}$.

2. Experimental methods

The YBCO films are deposited by *in situ* coevaporation in an atomic oxygen atmosphere using an ultra high vacuum evaporator equipped with electron beam heated sources for each of the Y, Ba and Cu metals. The cation rates are controlled by a quadrupole mass spectrometer which gives high compositional accuracy[2]. The substrates are polished (001)–oriented MgO single crystals. The resulting films are 350nm thick. The films are patterned by photolithography using a combination of argon ion beam milling and ethylene diamine tetra–acetic acid (EDTA) wet etching. After patterning the films are annealed at 500^{0}C in 1 bar of O_2 to improve contact adhesion and to re–oxygenate the patterned edges.

The standard resonator geometry is shown in figure 1, and is chosen so that the lines have characteristic impedances of 50Ω, with strip widths of 200μm, line spacings of 73μm and total line lengths of 8mm. The line spacings are around 2μm larger than designed due to the wet etch process. The values of T_c of the films are between 88–91K, with measured J_c(77K) in excess of 10^6Acm^{-2}.

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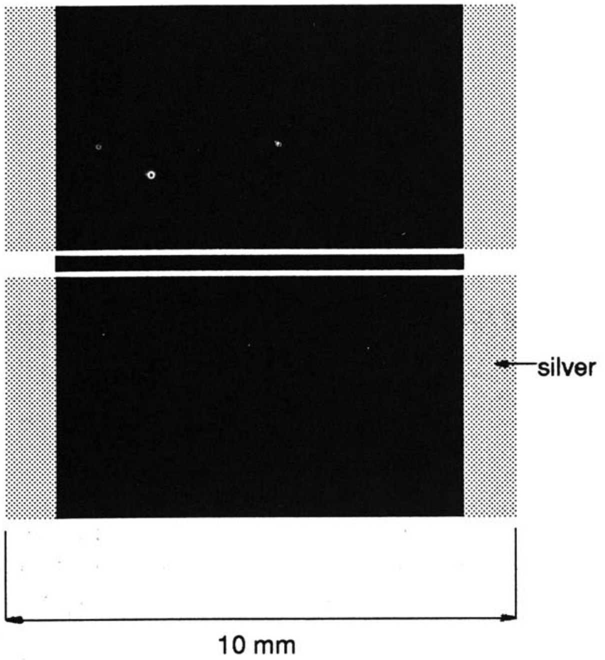

Figure 1. A scale diagram of the linear coplanar resonator.

We package the resonators in a brass housing and capacitively couple microwave power into the ends of the resonators using K–connector pins; coupling gaps are typically around 300μm long, and can be adjusted mechanically at room temperature. The ground plane ends of the resonators are silvered and electrical contact to the housing is aided by a thin layer of indium. The package is mounted in a closed cycle cooler and the transmitted microwave response is measured using a Hewlett Packard 8720A network analyser with computer control. At low temperatures we obtain a dynamic range in excess of 60dB for all of the modes presented in this paper.

At high fields the resonances are distorted, so measurement of the quality factor directly from the bandwidth of the response can be misleading. In these cases we measure the change in insertion loss of the resonance relative to the response at low power; we then calculate the bandwidth change from this change in insertion loss.

3. Results and analysis

Figure 2 illustrates the unloaded quality factor Q_0 as a function of temperature for the first two modes of a linear resonator at 7.97GHz. This resonator gave the highest Q_0 of those tested, at 7.97GHz ranging from 43000 at 13K, to 7000 at 77K.

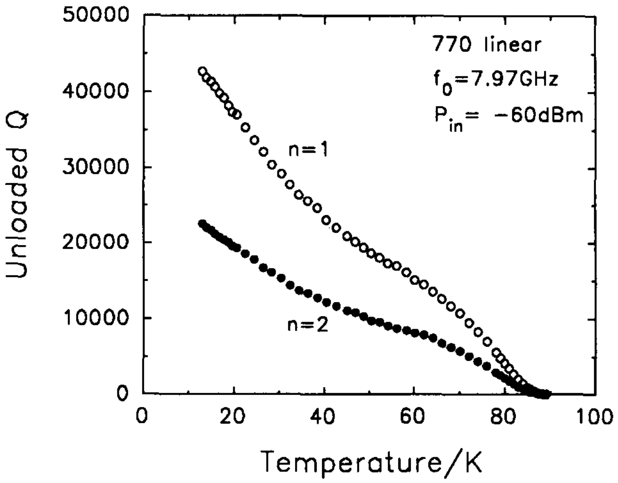

Figure 2. The unloaded quality factor Q_0 as a function of temperature for the first two modes of resonator 770.

At this point it is useful to introduce a normalised resonant frequency shift $\Delta f(T)/f(T)$, defined as $(f(T_0) - f(T))/f(T)$, where $f(T)$ is the resonant frequency at temperature T; T_0 is a fixed low temperature (usually around 12K), chosen as the origin for the frequency shift. The quantity $\Delta f(T)/f(T)$ is independent of frequency apart from very close to T_c. We carefully measure this quantity for as many modes as possible and use this data to estimate $\lambda(T)$ using the calculated current distribution in the resonator[1]. We calculate the current distribution using the method of Weeks et al. by dividing the resonator cross section into an array of parallel superconducting transmission lines[3, 4].

Since we can only reliably measure frequency shifts, we are unable to calculate $\lambda(0)$ for a single set of data for one resonator without first assuming a model variation of $\lambda(T)$. To avoid these assumptions we pattered two parallel resonators of different line spacings onto the same film, from which we were able to estimate $\lambda(T)$ absolutely[1], assuming that the film properties did not vary across the film surface. For the two films we have studied with multiple resonators we obtain $\lambda(0)$ in the range 180 – 220nm. However, we find that the temperature dependence of $\lambda(t)$ can be fitted by the function $\lambda(0)/(1-t^2)^{1/2}$ over the full temperature range, where $t = T/T_c$ (we will briefly discuss the physical basis of this form of $\lambda(T)$ later). For all of our single resonators we find that this function closely fits the data for $\lambda(t)$ in each, with values of $\lambda(0)$ in the range 160 – 230nm. The films with the lowest values of $\lambda(0)$ give resonators with the highest Q_0 and have the best power handling capabilities.

This procedure yields completely self-consistent results. We then calculate the value of R_S from the measured Q_0 and the calculated λ. $\lambda(T)$ has to be known very precisely for thin film planar resonators before $R_S(T)$ can be estimated since $R_S \propto \lambda^3$ and since the form of the current distribution (and hence the magnitude of the conductor loss) depends critically on the ratio of λ to the film thickness. However, we believe that our calculated values of R_S have a systematic error no greater than ±30%. (We actually quote this systematic error for our measurements; the random error is less than ±5%).

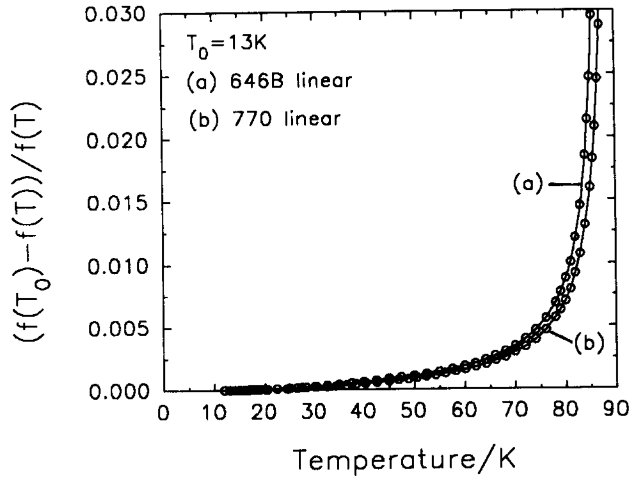

Figure 3. The quantity $\Delta f(T)/f(T)$ plotted for the fundamental modes of resonators 646B (curve (a)) and 770 (curve (b)) for low microwave input powers.

In figure 3 we plot $\Delta f(T)/f(T)$ for two linear resonators (denoted 770 and 646B). Sample 770 was grown onto a MgO substrate buffered with a 10nm layer of *in-situ* deposited MgO, with growth conditions carefully optimised to give a high T_c and dc critical current density. Sample 646B was an earlier film grown onto an unbuffered MgO substrate, with less well optimised growth conditions. Consequently, the dc properties of the two films differ, with $T_c = 90.2$K and $J_c(77\text{K}) = 2.5 \times 10^6 \text{Acm}^{-2}$ for sample 770, but $T_c = 88.2$K and $J_c(77\text{K}) = 1.4 \times 10^6 \text{Acm}^{-2}$ for 646B. We find plots like figure 3 extremely useful in qualitatively comparing the penetration depths of two otherwise identical resonators, without having to perform any detailed calculations. In figure 3 the data for $\Delta f(T)/f(T)$ of sample 770 lies below that of sample 646B, even taking into account the difference in T_c. We estimate $\lambda(0) = 160 \pm 15$nm for sample 770, with $\lambda(0)$ for sample 646B around 15nm larger.

In figure 4 we show the calculated $R_S(T)$ for the first two modes of both sample 770 and sample 646B for low microwave input power. The difference between R_S at 8GHz and 15K for the two samples is not large; we obtain values of $25 \pm 6\mu\Omega$ and $33 \pm 8\mu\Omega$ for 770 and 646B, respectively, which is almost accounted for by the difference in λ(15K) (since $R_S \propto \lambda^3$). At 77K the same respective values are $105 \pm 25\mu\Omega$ and $115 \pm 30\mu\Omega$. This difference is of little importance for low power microwave applications.

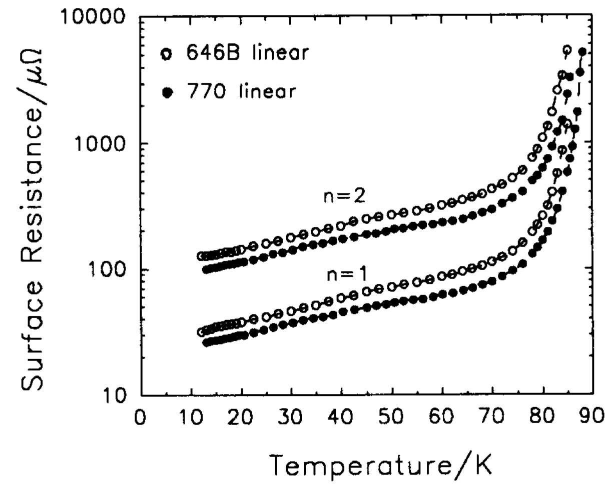

Figure 4. $R_S(T)$ of the first two modes of resonators 646B (open circles) and 770 (solid circles) at 7.95GHz and 7.97GHz, respectively.

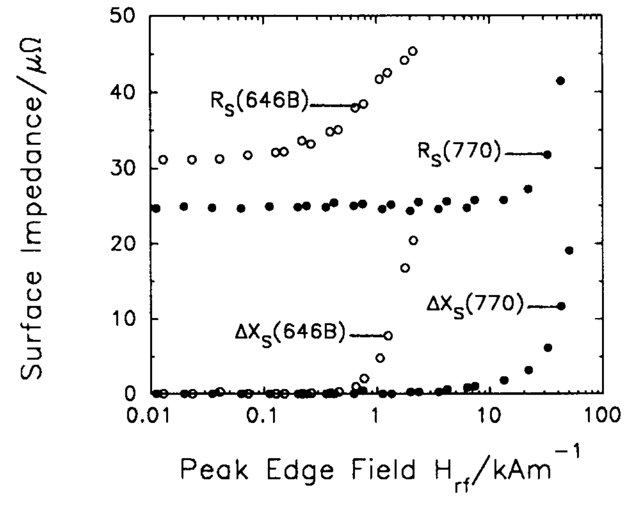

Figure 5. The non-linear surface impedance as a function of the peak magnetic microwave field H_{rf} at 8GHz and 15K for samples 646B (open circles) and 770 (solid circles).

However, in figure 5 we plot the dependence of the surface impedance $Z_S = R_S + iX_S$ as a function of H_{rf} at 15K, and here the difference in behaviour is much more pronounced. For sample 646B, Z_S increases rapidly above fields of 500Am^{-1} (where the total current on the central strip is around 5mA), but for sample 770 the response is independent of field up to fields of around $10^4 Am^{-1}$ (where the total strip current is around 0.1A, with an edge current density of around $4 \times 10^6 Acm^{-2}$). Note that at 15K we expect the lower critical field $H_{c1} \simeq 3 \times 10^4 Am^{-1}$.

4. Discussion and conclusions

The results obtained on a range of samples are consistent with the surface impedance and its power dependence being determined by the film growth conditions. We attribute the wide variations in power dependence as being due to crystal defects which occur at the growth stage. We have not optimised our film patterning or post annealing processes. The initial ion beam milling removes the YBCO and silver down to the substrate; the EDTA wet etch is intended simply to remove ion damaged material at the film edges, and the resulting edges are often irregular on the scale of $\sim 1\mu m$. For our earlier patterned films we believed that this process may have been limiting the resonator performance at large H_{rf} due to edge damage; however, these recent results imply that growth conditions limit the performance of patterned films, and not necessarily the patterning itself.

The temperature dependence of R_S for the samples 770 and 646B are very similar for low microwave input powers, with R_S continually decreasing at the lowest temperatures. The loss tangent of the MgO substrate should also continuously decrease as T decreases, but we find that Q_0 is very nearly proportional to $1/f$ at all temperatures, thus setting an upper limit of $\tan\delta \simeq 4 \times 10^{-6}$ below 50K; this loss is much smaller than the conductor loss. We see no dramatic decrease in R_S at low temperatures, unlike that observed recently in unpatterned films with optimised oxygen post annealing[5]. However, our absolute values of the low field R_S are only a factor of 2 or so higher than the best reported values for unpatterned YBCO at both 15K and 77K (e.g. [5]).

We calculate absolute values of $\lambda(0)$ to lie in the range 160–230nm for all of the resonators tested. A larger value of $\lambda(0)$ invariably leads to larger values of R_S and to enhanced non–linear effects at much lower values of H_{rf}; indeed, films having $\lambda(0) \simeq 230$nm show strong non–linear behaviour even at the lowest values of $H_{rf} \simeq 5Am^{-1}$. We can explain the large, variable value of $\lambda(0)$ and its anomalous temperature dependence reasonably well using the weakly coupled grain model[6, 7], which accounts for the additional field penetration into crystal defects (e.g. twin boundaries), in addition to the London penetration into the surrounding superconducting regions. A more quantitative discussion of this effect may be found in reference [1].

5. Summary

We find that Z_S of optimised patterned films differs little from that of unpatterned films, even at high power levels. Non–linear effects can be associated with film defects that appear to occur at the film deposition stage; film patterning results in little further damage. Optimisation of the oxygenation conditions during growth and any subsequent post annealing should further reduce the surface impedance and non–linear effects in the films, making them suitable for both high and low field microwave applications.

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