High-Temperature Superconducting Materials for High-Performance RF Filters

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This paper describes the development of high-Tc, superconducting YBCO films for high-performance RF filters. The use of a high-Q filter is expected to provide high selectivity and high sensitivity in the base stations of mobile telecommunication systems. We fabricated 2 GHz-band microstripline resonators by pulsed laser deposition of YBCO films and used them to study the relationships between the Q, microstructure, and film-thickness of YBCO films. A resonator consisting of 0.9 μm-thick epitaxial YBCO films on both sides of an MgO single-crystal substrate achieved an unloaded Q of 8×10^4 at 70 K, which is about 10 times higher than the Q of conventional filters. A 2 GHz-band microstripline bandpass filter using the high-quality films demonstrated superior characteristics with a very low insertion loss and steep cutoffs.

1. Introduction

Recently, many kinds of large-capacity, digital mobile telecommunication systems, for example, PDC, GSM, and IMT-2000 (which operates at around 2 GHz) have been introduced around the world. This introduction has made it necessary to make more efficient use of radio bandwidth. In the US, the allocation of frequency bands without guard bands to separate adjacent bands has lead to the radio frequency interference called the AB problem, even in the existing mobile telecommunication system. To solve this problem, some operators have equipped the receiving sub-units of their cellular base stations with superconducting filter sub-systems that include a low-noise amplifier (LNA) and a cryocooler that cools the amplifier down to about several tens of kelvins.[1)] Likewise, Japan and European countries will probably have a serious problem of interference between systems or service operators in the near future. Also, high-sensitivity base stations are predicted to be necessary for higher data transfer rates and/or larger base-station service areas.

A high selectivity and high sensitivity can be obtained in the receiving sub-units by using high-performance RF filters with a high Q value. **Figure 1** shows the simulated performance of several 9-pole microstripline bandpass filters with different unloaded Q values (Qu). Each filter contains nine resonators that are electromagnetically coupled with each other. The figure indicates that high-performance RF filters with a very low insertion loss and sharp cutoffs on both sides of their frequency curves require an unloaded Q of more than 10^4. However, it is difficult for conventional filters such as semi-coaxial type filters to achieve such a high Q, because their conductors are made of non-superconducting metals such as Cu, Ag, and Au. High-Tc superconducting (HTS) filters that

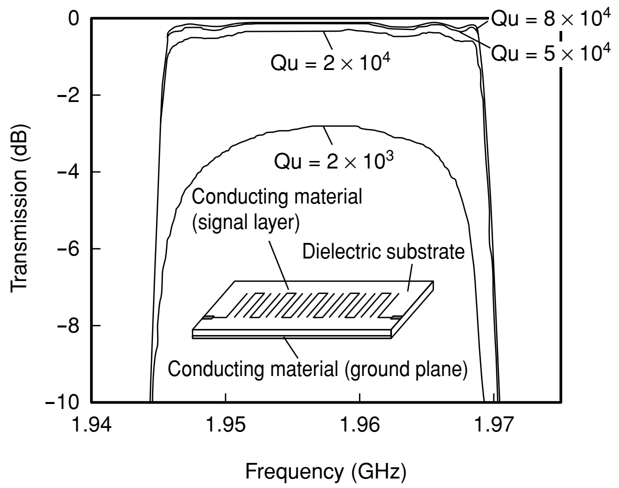

Figure 1
Simulated frequency responses of 9-pole microstripline bandpass filters with different unloaded Q values (Qu).

use HTS materials as a conducting material can have very high Q values due to their very low surface resistance Rs. For practical uses, however, a miniaturized filter with microstripline circuits is selected to reduce the load on the cryocooler. Accordingly, there is a need to develop HTS films on low-loss dielectric substrates for high-Q microstripline filters.

Many researchers have reported that the quality, especially the crystallinity, of HTS films affects their Rs.[2)-5)] Therefore, high-quality HTS films, for example, single-crystal films, were expected to have a very low Rs and therefore a high Q. Moreover, it was theoretically expected that making an HTS film thicker would be an effective way to obtain higher Q values in microstripline structures.[6)] However, the difficulty of acquiring high-quality thick HTS films has prevented us from clarifying the relationship between the Q, microstructure, and thickness of these films and thereby obtain higher Q values.

In this paper, we describe the development of $YBa_2Cu_3O_{7-\delta}$ (YBCO) HTS films deposited on MgO dielectric single-crystal substrates for high-performance RF microstripline filters. We also describe a 2 GHz-band microstripline bandpass filter that uses the YBCO films.

2. Development of high-quality YBCO films

2.1 Film deposition

As shown in Figure 1, to obtain higher Q values, a microstripline filter employs HTS films in the signal layer and also in the ground plane. Therefore, it should be possible to improve the performance by depositing high-quality HTS films on both sides of the substrate.

It is important to select a substrate that is suitable for RF applications and for growing YBCO films. For RF applications, magnesium oxide, MgO, is suitable because its dielectric constant ε_r is 9.7 and it has a low-loss tanδ of about 10^{-6}. On the other hand, the crystallographic lattice mismatch between MgO and YBCO is relatively large, so deposited YBCO films with a c-axis orientation tend to include in-plane misaligned grains that cause an increase in Rs. As mentioned in the introduction, we needed to make a high-quality thick film. Thick YBCO films with no cracks can be made because the thermal expansion coefficient of MgO is larger than that of YBCO. We therefore decided to deposit YBCO films on MgO substrates.

To investigate the relationship between the Q, microstructure, and film thickness of YBCO films, we prepared YBCO films of up to 1 µm thick using five types of growth conditions. The YBCO films (A to E) were grown on both sides of MgO (100) single-crystal substrates by pulsed laser deposition (PLD) using a KrF excimer laser.[7)] First, deposition was done on one side of the substrates. Then, the substrates were turned over and deposition was done on the other sides. (The deposition chamber had to be opened to turn the substrates over, so they were exposed to air at room temperature at this point.) During the depositions, the substrates were heated by radiation to about 700°C in oxygen. A YBCO ceramic target was ablated with a KrF excimer laser to form uniform large-scale YBCO films of up to 2 inches in diameter for 2 GHz-band microstripline filters. There was no further treatment after the PLD process.

2.2 Film characterization

Some of the factors that increase the Rs of HTS films have been researched, and it has been found that crystallinity has a particularly marked effect. HTS materials have an anisotropic, layered crystal structure that includes several CuO_2 sheets through which supercurrents prefer to flow. In microstripline resonators and filters, therefore, the CuO_2 sheets should be parallel with the dielectric substrate. Crystallography defines that the ab-plane of the HTS crystal structure is parallel with the CuO_2 sheet and its c-axis is normal to it.

First, to investigate the microstructures of the five types of YBCO films, we investigated their crystal structure and crystallinity by x-ray diffraction (XRD) using the θ–2θ method. **Figure 2** shows a typical XRD pattern of the YBCO films. The θ–2θ analyses showed that each film consisted of strongly c-axis-oriented grains that are normal to the MgO substrate. Therefore, each c-axis orientation of the films was evaluated by the XRD ω-rocking method using the (005) plane of the YBCO films. The full width at half maximum (FWHM) of the (005) rocking curve indicates the degree of c-axis orientation. We also estimated the average grain sizes on the film surface using polarized optical microscopy (POM). **Table 1** shows a summary of estimations of the crystal structure and crystallinity. This table indicates that there is no correlation between the average film-thickness and crystallinity. We measured the film thickness using a stylus profilemeter.

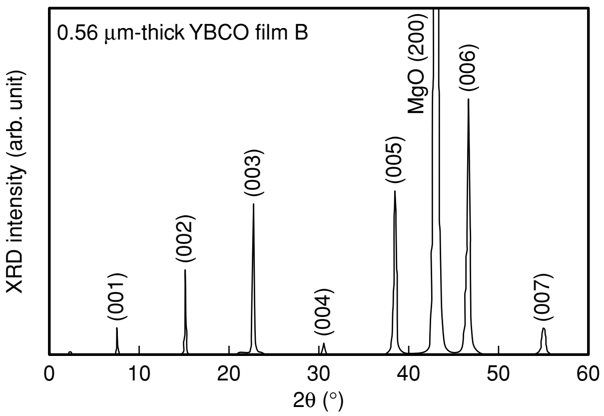

Figure 2
Typical XRD pattern of deposited YBCO film.[8)]

The orientation in the a-b plane is also important. We therefore evaluated the in-plane orientation of the films by XRD ϕ-scanning in the (103) plane of the YBCO films.[8)] The results for films B, C, D, and E are shown in **Figure 3**. As can be seen, these four films have large ϕ-scanning peaks every 90° and films C and D also have small peaks approximately midway between these large peaks. We performed (220) ϕ-scanning of the MgO substrates and found that films B and E grew epitaxially on the MgO substrate in the configuration of [100] YBCO // [100] MgO. On the other hand, films C and D included 45° rotated grains corresponding to the configurations of [110] YBCO // [100] MgO.

Table 1
Summary of estimations of crystal structure and crystallinity of deposited YBCO films.

Film	Average film-thickness (μm)	c-axis length (nm)	Amounts of note 1) a-axis grain	c-axis note 2) orientation (°)	Average grain-size (μm)
A	0.29	1.172	~ 0	0.75	1
B	0.56	1.171	0.018	0.57	3
C	0.77	1.171	0.022	0.79	2
D	0.85	1.173	0.016	0.80	0.5
E	0.92	1.171	0.015	0.40	3

note 1) Intensity ratio I(200) / I(006)
note 2) Full width at half maximum of (005) rocking curve

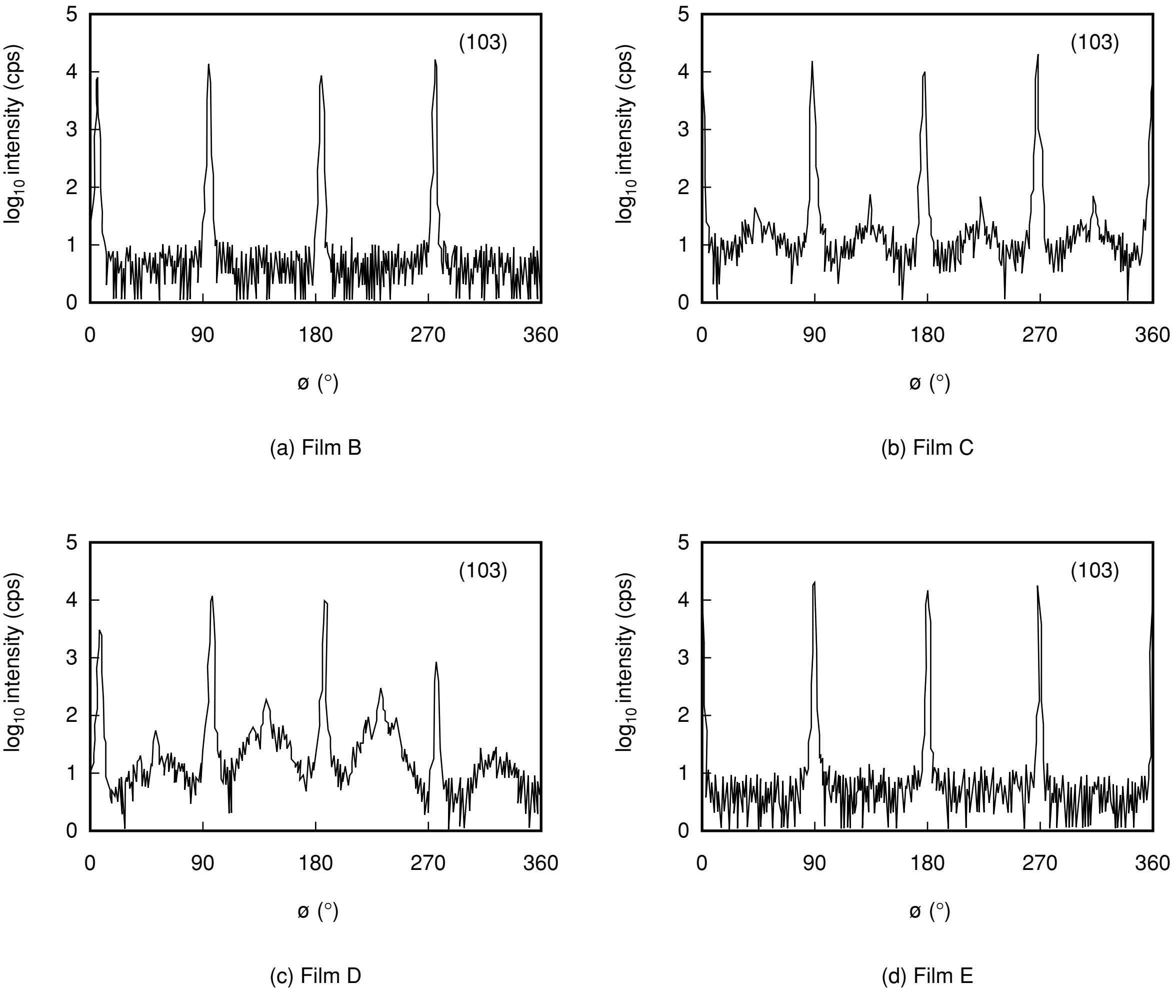

Figure 3
In-plane orientations of deposited YBCO films.[8)]

Furthermore, the cross-section microstructures of the YBCO films were observed by transmission electron microscopy (TEM).[8)] **Figure 4** shows some cross-sectional TEM images of the films. We found that films B and E have a dense structure, whereas the other films have a porous structure with Y211 (Y_2BaCuO_5) phase segregation. This indicates that the 211 phase may cause the formation of pores during film deposition. Field emission scanning electron microscopy (FE-SEM) also indicated that the pores occurred randomly throughout the thickness of the films.

Our investigation showed that we could classify the films into two types. One type has a high crystallinity with large grains and a dense struc-

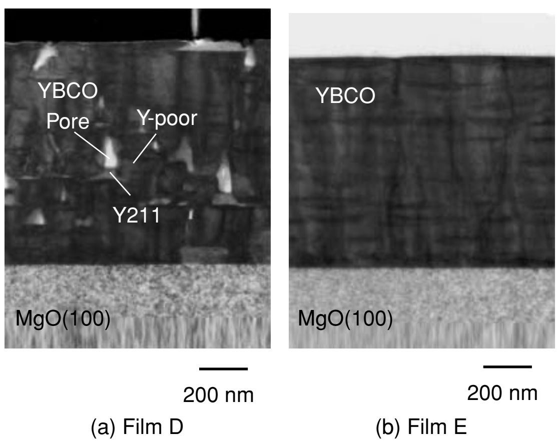

Figure 4
TEM images of cross section of deposited YBCO films.[8)]

ture; the other has a low crystallinity with small grains and a porous structure. We developed high-quality thick YBCO films of the first type that almost equal the crystallinity and structural homogeneity of a single crystal.

2.3 RF properties

There are many different methods for determining the RF properties of HTS films. Among them, the microstripline resonator method is suitable for practical applications. We therefore fabricated 2 GHz-band hairpin type microstripline resonators using our YBCO films to measure the RF properties of the films around 2 GHz. The YBCO film on one side of the substrate was patterned to form a signal layer, and the other side was used as a ground layer. Patterning was done with a specially developed process that does not damage the film. The fabrication process is described in the next section.

The unloaded Q (Qu) of the resonators, which showed resonances around 1.967 to 1.976 GHz at 70 K, was measured as a function of temperature with a small signal input. Next, we estimated the Rs and the London penetration depth λ_L, which indicates the rate at which the magnetic induction and the shielding supercurrent decay across the conductor. The estimations were made using the measured Qu values and the temperature dependence of the resonant frequency and were based on the method given in References 6) and 9).

Figure 5 shows Qu values of resonators made using the YBCO films shown in Table 1 as a function of normalized thickness $t/2\lambda_L$, where t is the measured thickness of the films. The two curves are drawn according to calculations with Rs values of 18 μΩ (type L) and 31.7 μΩ (type H). The type L films are films B and E, and the type H films are films A, C, and D. Figure 5 shows that films with the same Rs have a similar microstructure. We found that, in a microstripline structure, the Q increases when the film thickness is increased and decreases when the London penetration depth and/or Rs is increased. This means that a higher Q can be obtained by using thicker and higher quality YBCO films.

Figure 6 shows the Qu values of 2 GHz-band high-performance microstripline resonators we fabricated. These devices have high Qu values of up to 8×10^4 at 70 K and 1×10^5 at 60 K, which are about 10 times higher than the Qu values of conventional resonators. We achieved these high Qu values by using 0.9 μm-thick films with an extremely low Rs. By comparison, a resonator sample having the same structure but made with

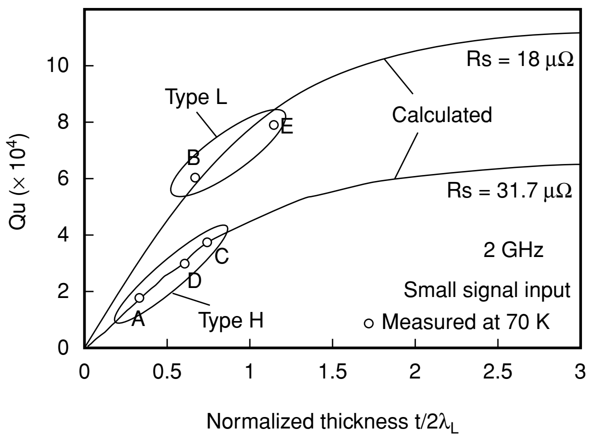

Figure 5
Unloaded Q (Qu) of YBCO film resonators with different normalized thicknesses, $t/2\lambda_L$.

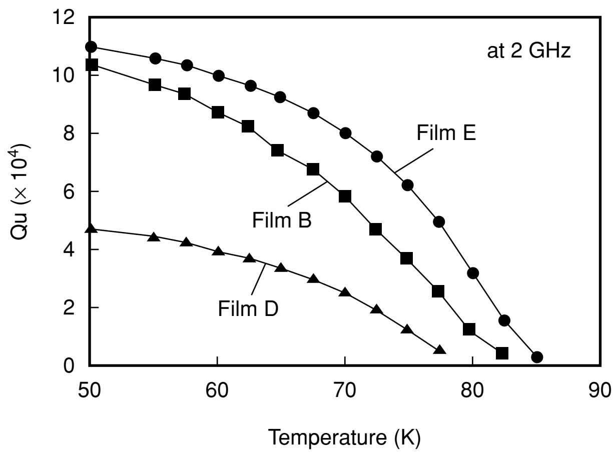

Figure 6
Temperature dependence of unloaded Q (Qu) of deposited YBCO films.

4 µm Cu films and an Al_2O_3 ceramic substrate has a Q of only 4×10^2 at 70 K.

3. RF microstripline filters using YBCO films

The previous section described the relationship between the Q, microstructure, and film thickness of the high-quality thick YBCO films we developed. Next, we used these films to fabricate some high-performance, 2 GHz-band microstripline filters. The element resonators of these filters have a hairpin structure and therefore can be made quite small. One of the methods we used for fabricating these RF microstripline filters is as follows:

1) Deposit YBCO film on both sides of a 2-inch MgO(100) substrate,
2) Pattern one side using photolithography and wet-etching, and use the other side as a ground plane.
3) Form Ag electrodes at the edges of the feeder-line by evaporation.
4) Cut the substrate to the required dimensions.
5) Mount the substrate in a metal housing containing SMA connectors, with the electrodes making mechanical contact with the SMA pins.

Figure 7 shows a 2 GHz-band 9-pole bandpass filter with its top cover removed. When in use, the filter is placed in contact with the cold plate of a cryocooler. The filter characteristics were measured as a function of temperature. **Figure 8** shows the transmitted and reflected responses of the filter at 70 K. The filter has superior characteristics with a minimum insertion loss of less than 0.1 dB and steep cutoffs on both sides. These responses can be very closely simulated by assuming that Qu is 8×10^4, which indicates we can now produce high-quality thick YBCO films with extremely high Q values and therefore produce very high performance filters.

4. Conclusion

We have developed YBCO high-Tc superconducting films for high-performance RF filters.

To investigate the relationship between the Q, microstructure, and film-thickness of YBCO films, we prepared YBCO films with a film thickness of up to 1 µm using different growth conditions. We grew high-quality thick YBCO films that almost equal the crystallinity and structural homogeneity of a single crystal.

Next, using the new YBCO films, we fabricated 2 GHz-band microstripline resonators and

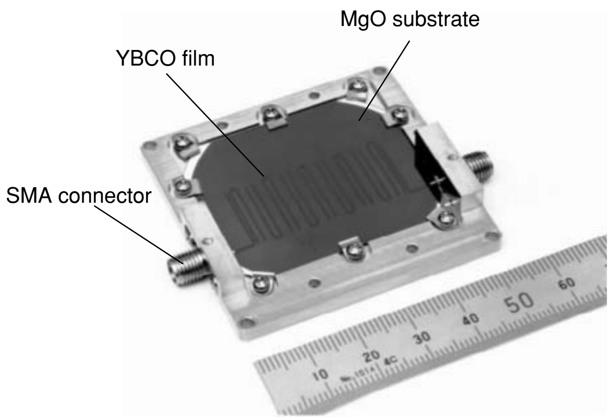

Figure 7
2 GHz-band 9-pole microstripline bandpass filter fabricated using YBCO films.

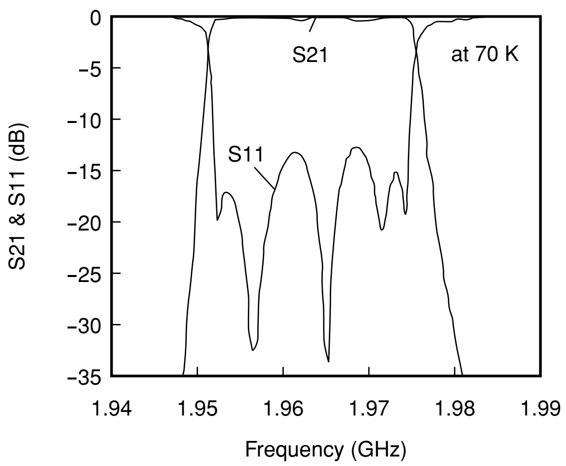

Figure 8
Responses of 2 GHz-band 9-pole microstripline bandpass filter at 70 K.

evaluated their performance. The results indicated that films with the same Rs have similar microstructures. More importantly, we found that, in a microstripline structure, the Q increases when the film thickness is increased and decreases when the London penetration depth and/or Rs is increased. Based on this work, we fabricated a microstripline resonator that consisted of an MgO single-crystal substrate with 0.9 µm-thick YBCO epitaxial films on both sides. This device achieved an unloaded Q of 8×10^4 at 70 K, which is about 10 times higher than the Q of conventional filters such as the semi-coaxial type filters. We also fabricated a 2 GHz-band microstripline bandpass filter using high-quality thick films that demonstrated superior characteristics with a very low insertion loss and steep cutoffs on both sides of its frequency curve.

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