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New devices of the system of TiO_2 sandwiched by Bi-based oxide superconductor

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Abstract

We investigated the behavior of the system of dielectric material sandwiched by the Bi-based oxide superconductor, under microwave irradiation. The dielectrics were TiO_2, $CaTiO_3$ and forsterite. For comparison of the superconductor functions, we prepared a sample in which TiO_2 was sandwiched by forsterite. The resonance frequency of the system was 6–9 GHz, corresponding to dielectrics and the Q values were 300–400 at room temperature and 2000–5000 in liq.N_2. Furthermore, it was found that the three resonance frequencies existed having differences of 0.003 GHz among them.

Keywords: Dielectric properties; Functional applications; Oxide superconductors; TiO_2

1. Introduction

Microwave devices using dielectrics have been developed for mobile communication systems, band-pass filters, and ceramic antennas and have been employed for higher frequency usage such as GHz range. The high T_c (transition temperature) oxide superconductor has been used for wires and tapes, but has not been a big seller although the high-Q coplanar microwave resonator[1] and low-phase-noise superconducting oscillators[2] have been developed in the past 10 years. Tamura et al. developed the filters of cellular base stations with thick film using Bi2223.[3] As a new application, there is a microwave irradiation associating with Josephson plasma resonance which is a vibration mode of Cooper pairs through the tunnel effect. Regarding the Bi-based oxide superconductor, a single crystal was used for the measurement of surface resistance at 45 GHz.[4] New applications of the high T_c oxide superconductor must be developed.

We have studied to develop a system dielectrics, such as TiO_2, with Bi-based oxide superconductor.[5,6] We found that the system of bulk type has a higher Q value than that in Tamura et al.'s report[3] even at room temperature.

In the present report, we have two objectives: one is to determine the function of the superconductor in the system under microwave irradiation and the other is to develop the dielectric resonator system with the oxide superconductor having the improved performance. The systems that we investigate are superconductor/TiO_2/superconductor, forsterite/TiO_2/forsterite and $CaTiO_3$/TiO_2/$CaTiO_3$.

2. Experimental

The dielectric powders of TiO_2 and $CaTiO_3$ (Fuji Titanium Industry Co., Ltd) were compacted at 192 MPa, and then the former was sintered at 1523 K and the latter at 1623 K for 2 h. Both pellets were cut to the required size for forming the dielectric system. $Bi_2Sr_2Ca_2Cu_3Ox$ (Institute of Kusaka Rare Metal) was pressed at the same pressure as the dielectrics, followed by sintering for 24 h at 1133 K. For the network analyzer using HP8510B, the ratio of total length (L) to diameter (D), L/D should be more than 0.4 in the $TE_{01\delta}$ mode. Each sandwiched system such as superconductor/TiO_2/superconductor, forsterite /TiO_2/forsterite or $CaTiO_3$ / TiO_2/ $CaTiO_3$ (hereafter, ① SC/TiO_2/SC, ② F/TiO_2/F and ③ CT/TiO_2/CT, respectively), shown in Fig. 1, is set in the cavity for the measurement of microwave properties. The systems are also used to analyze the

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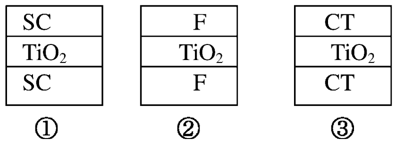

Fig. 1. The three sandwiched systems.

temperature dependence of relative permittivity, resonant frequency and quality factor (Q value) in the temperature range from 100 K to 300 K.

3. Results and discussion

3.1. Relative permittivity

TiO_2 has a relative permittivity of about 100, forsterite 85, and $CaTiO_3$ 140 at 1 MHz. These relative permittivities changed to around 35 at 6 GHz for all three systems at room temperature. Since the resonance frequency was confirmed using the following equation,[7] it can be applied to our system. For example,

$$f = \frac{c}{D}\sqrt{\frac{1.2}{\varepsilon_r}} = \frac{3.0 \times 10^8}{8.53 \times 10^{-3}}\sqrt{\frac{1.2}{35}} = 6.5 \times 10^9 \qquad (1)$$

in the case of forsterite having a diameter of 8.53 mm. The system of $SC/TiO_2/SC$ had the almost same resonant frequency of 6.4 GHz.

The temperature dependences of relative permittivity are shown for each system in Fig. 2.

The temperature coefficient (τ_f) is generally defined as

$$\tau_f = \frac{1}{f_{293}} \frac{f_{313} - f_{233}}{\Delta T} \times 10^6 \quad (\mathrm{ppm/K}) \qquad (2)$$

where f_{313} and f_{233} are resonant frequencies at temperatures of 313 and 233 K, respectively.

ΔT is 80 K. Within the narrow range of 233–313 K, all the systems showed a temperature coefficient of almost 0 ppm/K. Furthermore, by expanding the temperature range such as liq. N_2 temperature to 233 K, the TiO_2 system sandwiched by SC (①) indicated a temperature coefficient (τ_f) of 27.4 ppm/K, and 80.6 ppm/K was obtained for the system ②.

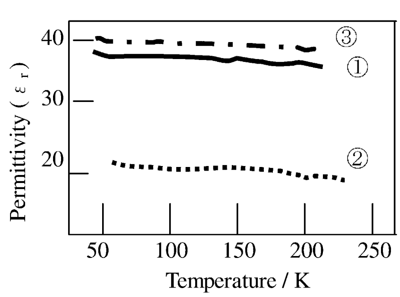

Fig. 2. Temperature dependences of relative permittivity for each system at liq.N_2 temperature to 233K.

Furthermore, forsterite alone showed the temperature coefficient of 274 ppm/K, and the τ_f of TiO_2 alone is usually said to be 450 ppm/K.[7] The value of τ_f was decreased by the formation of system with a slightly negative coefficient. Therefore, we can use TiO_2 as a good dielectric resonator in terms of temperature stability and permittivity by forming the system such as ② $F/TiO_2/F$ described above.

When comparing ① $SC/TiO_2/SC$ with ② $F/TiO_2/F$, the function of the superconductor in the system is distinct; less energy is lost from the system in liq.N_2 atmosphere when microwaves are irradiated to the system, because the superconductor conserves the magnetic energy of microwaves in the dielectric system due to its diamagnetic property.

3.2. Resonant frequency

Fig. 3 shows temperature dependences of resonant frequency in the SC ① system. Resonant frequency is basically determined by the shape of the system, as shown in Eq. (1). In our system, the thickness ratio, λ, of dielectric (TiO_2) to SC, F or CT has an effect on the resonant frequency, as discussed in Ref 5. There was only a slight difference in resonant frequency between λ = 0.79 and λ = 0.82, Furthermore, the λ = 0.5 indicates the maximum value of 6.3 GHz. The SC/forsterite/SC system was investigated together with the $SC/TiO_2/SC$ system in order to compare the effect of λ on the resonant frequency, as shown in Fig. 4. Here, the maximum value of 6.5 GHz is at λ = 0.55, which agrees with that of the $SC/TiO_2/SC$ system as well as the value described in Ref 5.

3.3. Quality factor (Q value)

The Q value (reciprocal of tan δ) is important as a general quality of the dielectric devices and the product of Q with resonant frequency, $Q \times f$, is frequently used for dielectric performance under microwave irradiation. Considering the ac-equivalent circuit in the system, dielectric conductivity, σ, by

$$\sigma = \omega \varepsilon_r \varepsilon_0 \tan\delta \quad (\mathrm{S/m}) \qquad (3)$$

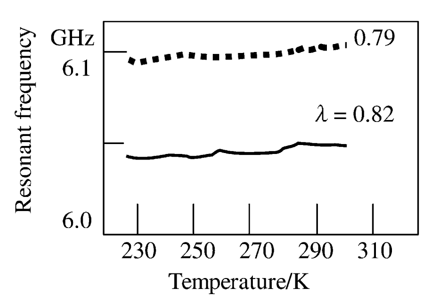

Fig. 3. Temperature dependences of resonant frequency in SC/ TiO_2/ SC system, λ (thickness ratio of TiO_2 to SC) = 0.79, 0.82.

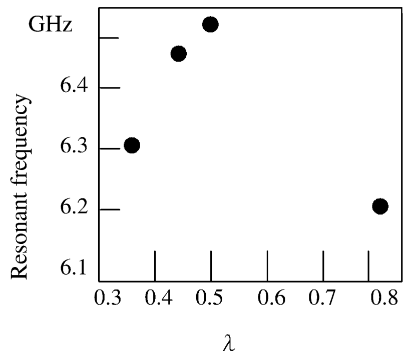

Fig. 4. Resonant frequency changes against thickness ratio, λ, of forsterite to SC.

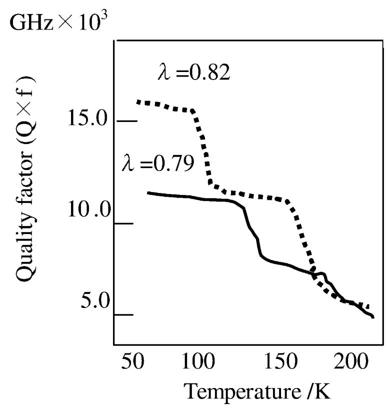

Fig. 5. Temperature dependences of quality factor for different λ, (TiO_2 to SC).

where $\omega=2\pi f$ (frequency), ε_r is relative permittivity, $\varepsilon_0=8.854\times10^{-12,}$ and δ is phase delay. In liq.N_2 atmosphere, ε_r increased slightly, as shown in Fig 2.

Furthermore, Q is described in the circuit which includes resistance R, inductance L and capacitance C as

$$Q=\frac{1}{R}\sqrt{\frac{L}{C}} \tag{4}$$

When ε_r is increased, σ increases larger as determined by Eq. (3), therefore, resistivity decreases resulting in a higher Q value according to Eq. (4).

In Fig. 5, the specimen with thickness ratio of 0.82 had 6.9 GHz resonant frequency, while the system with $\lambda=0.79$ had 5.8 GHz. As a result, the quality factor was larger in the specimen having greater thickness of the dielectric. It is worth noting that abrupt increases of $Q\times f$ are observed at approximately 130 K for $\lambda=0.79$ and at 170 K for $\lambda=0.82$.

The other specimen of the F/TiO_2/F system showed interesting behavior; first, the three spectra of resonant frequency were found to have the difference of about 200 MHz and secondly, one of the resonant frequencies showed the abrupt increase of $Q\times f$, as illustrated in Fig. 6, in which the largest value of more than 40,000 was observed.

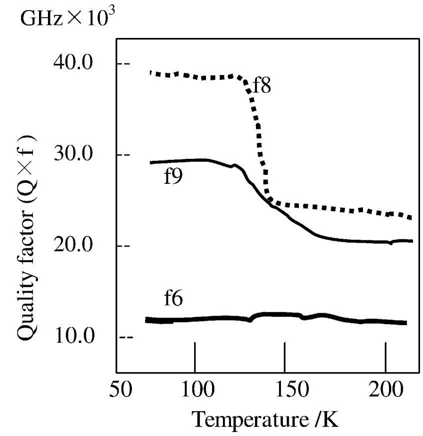

Fig. 6. Temperature dependences of quality factor for the F/TiO_2/F system. The notations of $f6$, $f8$ and $f9$ represent peak between 5 to 7, 7 to 9 and 8 to 10 GHz, respectively.

As mentioned above the quality factor increased at around 130 K in spite of the fact that this system does not include a superconductor. The reason has not yet been clarified.

Secondly, three peaks of resonant frequency appeared. We postulate that because forsterite includes MgO and SiO_2 as two major constituents, the F/TiO_2/F system is composed of three ceramics (including TiO_2), each having different permittivities. On the other hand, only TiO_2 functions as a capacitor in the SC/TiO_2/SC system, resulting in only one peak of resonant frequency.

4. Conclusion

Dielectrics were sandwiched by the Bi-based oxide superconductor and subjected to microwave irradiation. The maximum resonant frequency was obtained by the forsterite/TiO_2/forsterite system, showing 8 GHz with a $Q\times f$ value of 40,000 and τ_f of 81 ppm/K in liq.N_2 atmosphere. Furthermore, the superconductor showed good temperature stability. The TiO_2 system sandwiched by SC indicated a temperature coefficient (τ_f) of 27.4 ppm/K, and 80.6 ppm/K was obtained for the forsterite/TiO_2/forsterite system.

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