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ARTICLE

Dielectric thermometer by using the quantum paraelectricity for microcalorimeter

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The electric capacitance of a $SrTiO_3$ thin film was measured at frequencies from 1 to 100 kHz by using an impedance analyzer with four-terminal method in the temperature range from 100 to 200 mK. The values of the electric capacitance exhibited large temperature dependence below temperature of 110 mK. The temperature dependence of the electric capacitance is expected to be utilized for the dielectric thermometers of the microcalorimeter.

KEYWORDS: microcalorimeter, $SrTiO_3$ thin film, the dielectric thermometer, the temperature dependence of the dielectric constant

I. Introduction

A microcalorimeter is a radiation particle detector indicating the energy of incident particle by measuring a rise in temperature of an absorber. A sensitive thermometer is an important component of the microcalorimeter. Various types of thermometers for the microcaloriemeter have been developed and exhibited excellent energy resolution below 10 eV of FWHM in X-ray detection[1)].

A dielectric thermometer has been proposed for microcalorimeter utilizing the dependence of the dielectric constant on temperature[2)]. The temperature rise induced by the energy deposition of the incident radiation is converted into electric charge proportional to the change in dielectric constant of the dielectric thermometer.

A $SrTiO_3$ (STO) thin film was developed for a cryogenic thermometer[3)]. The STO thin film has a potential of a sensitive thermometer for the microcalorimeter. In this work, the electric capacitances and the loss factors of the STO thin film were measured at frequencies from 1 to 100 kHz in the temperature range from 100 to 200 mK.

II. Dielectric microcalorimeter

Figure 1 shows the schematic drawing of the operating concept of the dielectric microcalorimeter with the heat capacitance C_V and the electric capacitance C_d. The thermal link with the conductance G connects the dielectric calorimeter to the cold stage maintained at the base temperature T_0. The temperature of the dielectric calorimeter is raised by the energy deposition of the incident particle, and falls down to T_0 with time constant of thermal relaxation $\tau = C_V/G$. The transient temperature change of the dielectric calorimeter by absorbing the energy E of the incident particle is expressed by

$$\Delta T(t) = T(t) - T_0 = \frac{E}{C_V}\exp\left(-\frac{t}{\tau}\right). \qquad (1)$$

The electric capacitance C_d of the dielectric calorimeter changes with the temperature $T(t)$. The electric charge Q, stored in the dielectric material by applying a constant DC voltage V_B, alters with changing of C_d. Therefore the energy E of the incident particle is converted into a change in the electric charge, given as

$$\begin{aligned}\Delta Q = V_B \Delta C_d &= V_B\left(\frac{dC_d}{dT}\right)\Delta T \\ &= \frac{EV_B}{C_V}\left(\frac{dC_d}{dT}\right)\exp\left(-\frac{t}{\tau}\right). \qquad (2)\end{aligned}$$

To generate a pulse signal from the detector, ΔQ is collected by the charge sensitive preamplifier. The feedback-resistance and capacitance of the preamplifier are R_f and C_f, respectively. The time constant of the preamplifier is assumed to be $C_f R_f \gg \tau$. Finally, the output voltage signal of the incident particle detection by the dielectric microcalorimeter is given by

$$\begin{aligned}V_{out} &= \frac{\Delta Q}{C_f} \\ &= \frac{EV_B}{C_f C_V}\left(\frac{d\ln C_d}{dT}\right)C_d(T_0)\exp\left(-\frac{t}{\tau}\right). \qquad (3)\end{aligned}$$

The energy solution ΔE of the dielectric microcalorimeter is defined by[4)]

$$\Delta E(FWHM) = 2.35\sqrt{k_B C_V T_0^2/\alpha}, \qquad (4)$$

where k_B is Boltzmann constant and α is the sensitivity of the dielectric microcalorimeter expressed by

$$\alpha = \frac{d(\ln C_d)}{d(\ln T)}. \qquad (5)$$

From eqs. (4) and (5), the energy resolution of the dielectric microcalorimeter improves with increasing the value of α.

The dielectric microcalorimeter has advantages of suppressing the Johnson noise and the Joule heat generation in the device.

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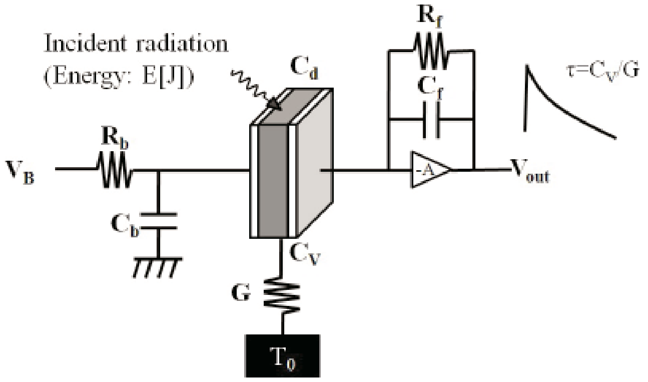

Fig. 1 Operating concept of the dierectric microcalorimeter. (V_B: a constant DC voltage applied, R_b and C_b: low pass filter, C_d: electric capacitance, C_V: heat capacitance, G: heat conductance, T_0: operating temperature, R_f and C_f: feedback-resistance and capacitance of the preamplifier, V_{out}: output voltage signal, τ : time constant)

III. The epitaxially grown STO thin film

The STO is a typical quantum paraelectric material. The dielectric constant of the quantum paraelectric materials increases with cooling down. However the quantum paraelectric materials do not undergo ferroelectric transition at low temperatures because of quantum fluctuation, but holds the high values of the dielectric constant[5]. A certain kind of the quantum paraelectric materials was found to exhibit the temperature dependence of the dielectric constant around 100 mK[6].

A STO thin film was developed for the capacitance cryogenic thermometer at National Institute of Advanced Science and Technology[3]. The STO thin film has a potential of a sensitive thermometer for the microcalorimeter. The capacitance thermometer consists of epitaxially grown STO thin film between two $YBa_2Cu_3O_{7-\delta}$(YBCO) electrodes.

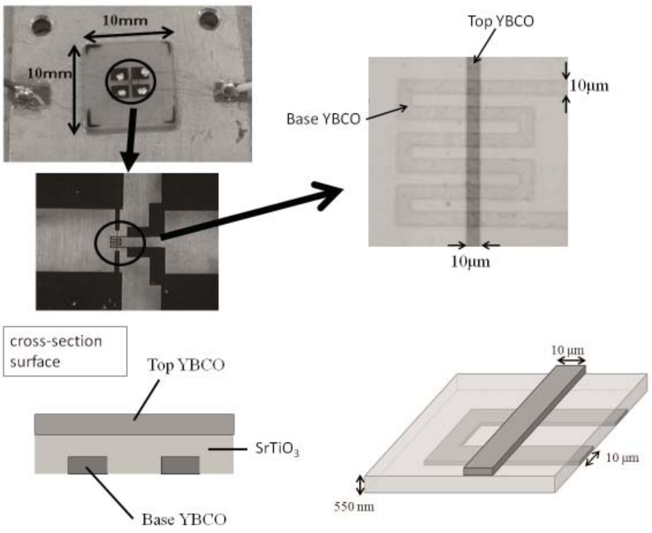

Fig. 2 The fabricated epitaxially grown YBCO/STO/YBCO

Figure 2 shows photographs of the fabricated epitaxially grown YBCO/STO/YBCO. The epitaxially grown STO thin film of 550 nm thick was deposited on the meandering shaped line 10 μm wide of the YBCO base electrode. As shown in Fig. 2, six parallel capacitors are produced at intersections between the top and the base electrodes. The electric capacitance at 300 K was 14 pF.

A liquid-helium-free ^{3}He-^{4}He dilution refrigerator was employed to cool the dielectric thermometer. The liquid-helium-free ^{3}He-^{4}He dilution refrigerator was manufactured by Taiyo Nippon Sanso Corporation. A schematic drawing of the liquid-helium-free ^{3}He-^{4}He dilution refrigerator is illustrated in **Fig. 3**.

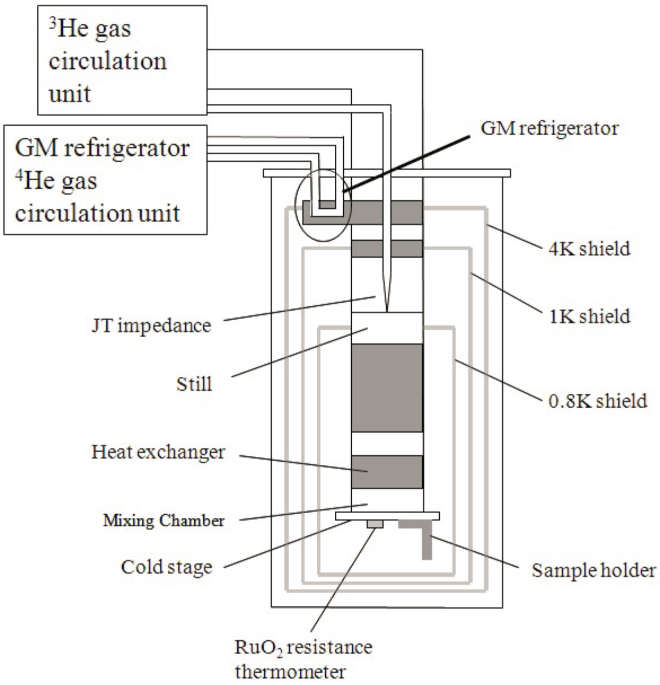

Fig. 3 Schematic drawing of the liquid-helium-free 3He-4He dilution refrigerator

The ^{3}He-^{4} He dilution refrigerator is operated without consuming liquid helium by loading a Gifford-McMahon (GM) cooler.

The STO thin film chip was glued on the copper plate with the GE7031 varnish. The copper plate was placed on the holder bolted to the cold stage of the refrigerator.

IV. The temperature dependence of dielectric constant at various frequencies

The electric capacitance and the dissipation factor of the STO thin film were measured at frequencies from 1 to 100 kHz by using an impedance-analyzer with four-terminal method in the temperature range from 100 to 200 mK. **Figure 4** shows relationship between obtained real values of the electric capacitance and the temperature. Since the value of the electric capacitance of the STO thin film was measured to be 14 pF at 300 K, the quantum paraelectricity of the STO thin film was confirmed by a growth in the electric capacitance. Due to

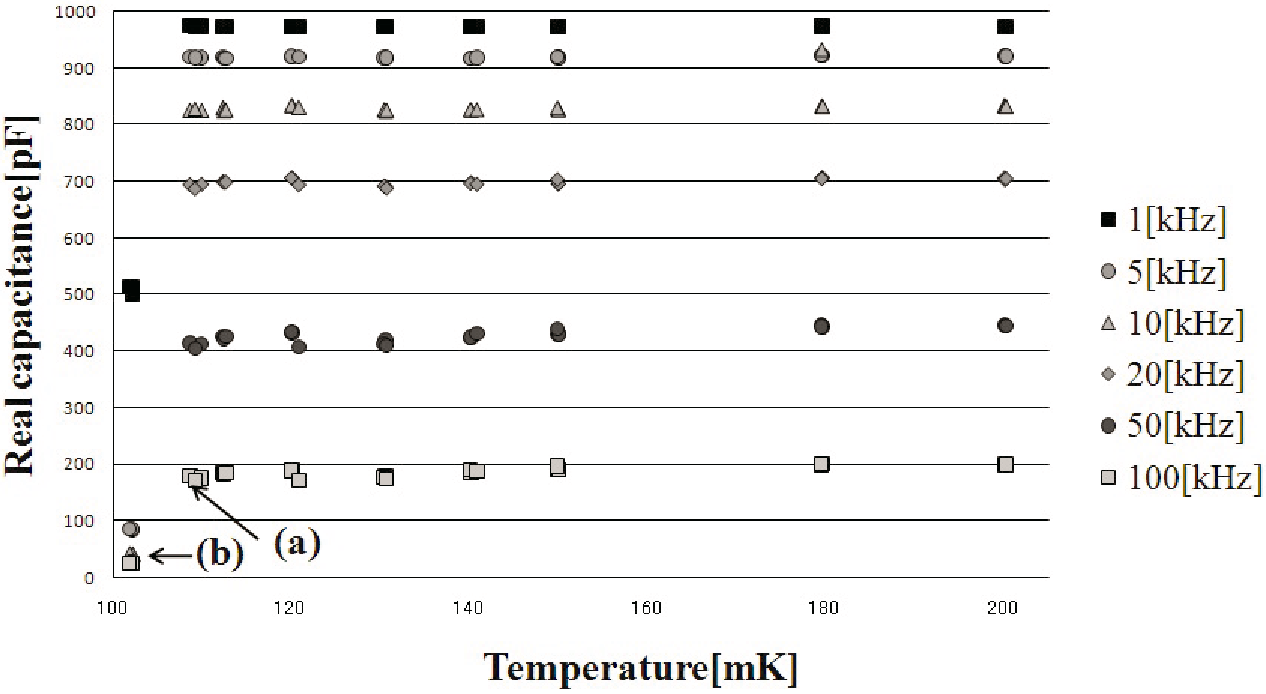

Fig. 4 Variation of the real electric capacitance as a function of temperature. ((a): 108.4 mK, 178.9 pF, 100 kHz, (b): 102.0 mK, 25.1 pF, 100 kHz. The sensitivity of the thermal sensor α is 28.7±4.1.)

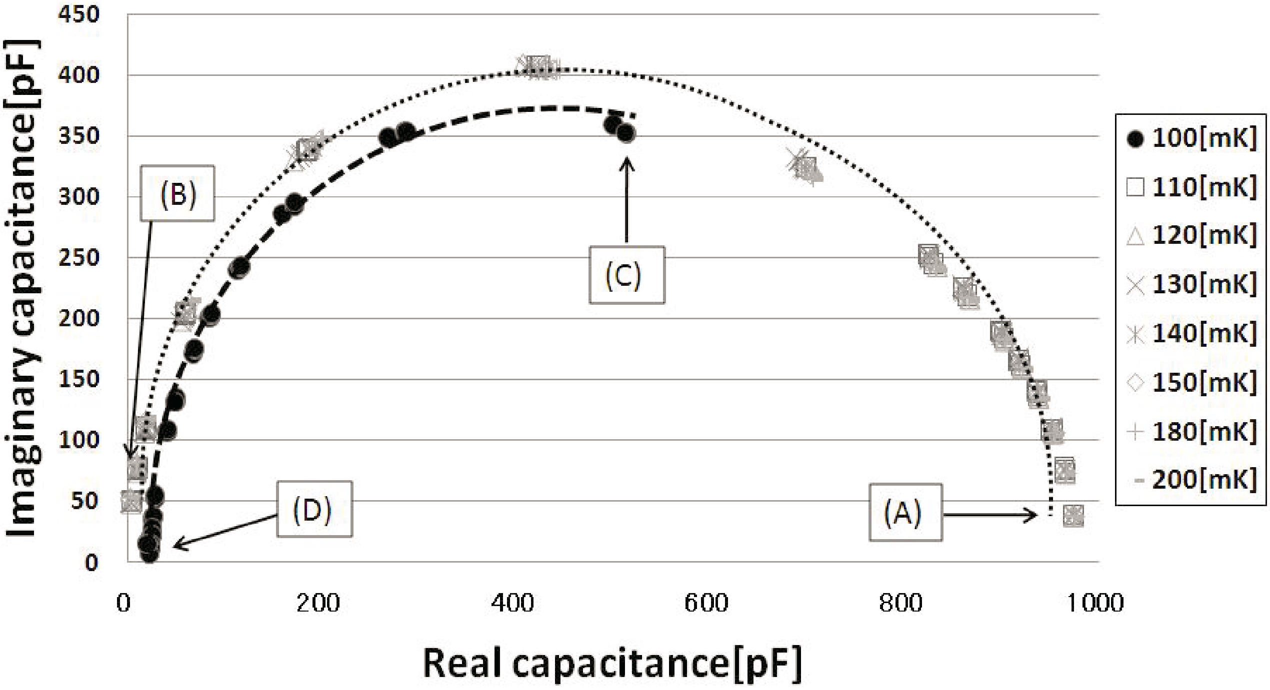

Fig. 5 Relationship between the imaginary and real components of electric capacitance. ((A): 110-200 mK, 1 kHz, (B): 110-200 mK, 100 kHz, (C): 100 mK, 1 kHz, (D): 100 mK, 100 kHz.)

the quantum paraelectricity the electric capacitance holds constant values in the temperature range from 110 mK to 200 mK. At temperatures below 110 mK, values of the electric capacitance decrease with temperature. A change in values of the electric capacitance implies a violation of the quantum paraelectricity.

In Fig. 4, (a) are three points at temperature 110 mK and (b) are three points at temperature 100 mK, at the frequency

100 kHz. These six points were converted into the double logarithm, and the inclination, i.e., the sensitivity for the dielectric microcalorimeter α was calculated by the least squares method. The sensitivity α is estimated to be 28.7±4.1 at frequency of 100 kHz. The energy resolution of the dielectric microcalorimeter is expected to be 3.3±0.2 eV of FWHM value with assuming the value of the heat capacitance of the dielectric thermometer to be 10 ^{11} J/K.

Complex electric capacitance was obtained from experimental values of the real electric capacitance and the dissipation factor. **Figure 5** shows relationship between the imaginary and real components of electric capacitance. Real components indicate the actual electric capacitance, while imaginary components correspond to the product of the actual electric capacitance and the dissipation factor.

In Fig. 5, the point (A) was obtained at the frequency of 1 Hz in the temperature range from 110 to 200 mK. With increasing frequency, experimental points moved counterclockwise from the point (A) along the circular arc and arrived at the point (B) at the frequency of 100 kHz. On the other hand the point (C) was obtained at the frequency of 1 kHz at a temperature of 100 mK. With increasing frequency, experimental points moved counterclockwise from (C) and arrived at the point (D) at a frequency of 100 kHz. Change in trajectories in Fig. 5 would imply a break in the quantum paraelectricity in the temperature region from 100 to 110 mK.

V. Conclusion

The electric capacitance of the epitaxially grown $SrTiO_3$ thin film was measured at frequencies from 1 to 100 kHz by using an impedance-analyzer with four-terminal method in the temperature range from 100 to 200 mK. The $SrTiO_3$ thin film exhibited the quantum paraelectricity in temperature range from 110 mK to 200 mK. The electric capacitance was found to decrease with temperatures below 110 mK. The sensitivity α of the dielectric microcalorimeter was evaluated to be 28.7±4.1 at frequency 100 kHz. The energy resolution of the dielectric microcalorimeter expected 3.3±0.2 eV of FWHM value assuming the value of the heat capacitance of the dielectric thermometer to be 10 ^{11} J/K.

Frequency characteristics of the electric capacitance was found to change in profile of obtained relationship between the imaginary and real components of electric capacitance at a temperature of 100 mK.

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