

RF DIELECTRIC PROPERTIES OF SiC CERAMICS AND THEIR APPLICATION TO DESIGN OF HOM ABSORBERS

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Abstract

The KEKB ARES cavity is equipped with two types of HOM absorbers, which are made of different commercial products of the alpha-type SiC ceramics. Their dielectric responses to the RF frequency show the dielectric relaxation properties. These properties can be explained by the polycrystal structure model with electrically conductive grains and non-conductive grain boundaries. In this article, the RF dielectric properties of the SiC ceramics are discussed together with the application to HOM absorbers.

INTRODUCTION

The KEKB ARES cavity [1] is equipped with two types of HOM absorbers, which are made of different commercial products of the alpha-type SiC ceramics sintered under atmospheric pressure. One absorber is bullet-shape SiC ceramics [2] and the other is a tile one [3]. In this article, we call the former and latter SiC materials “SiC-A” and “SiC-B”, respectively. In addition, the permittivity ϵ and the relative permittivity ϵ_r are expressed as follows; $\epsilon = \epsilon' - j \epsilon''$, $\epsilon_r = \epsilon / \epsilon_0 = \epsilon'_r - j \epsilon''_r$.

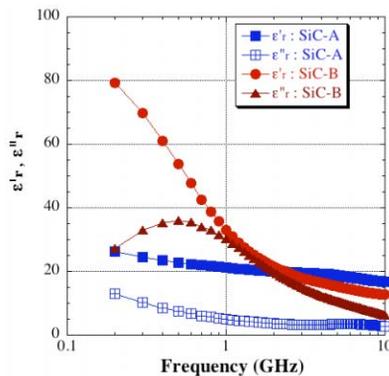


Figure 1: Typical permittivities of SiC-A and SiC-B.

In designing a HOM load, we should choose an absorbing material with an appropriate dielectric constant in the HOM frequency range. The RF properties of an absorber is similar to those of a dielectric waveguide. For example, the bullet-shaped absorber looks like a dielectric rod whereas a tile absorber like a dielectric slab. The electric field of the propagating mode in the absorber, for example the HE_{11} mode for a dielectric rod, is largely affected by the real part ϵ' related to the property of the surface wave [4]. Therefore, ϵ' is an important parameter for the absorber design as well as ϵ'' the imaginary part related to the dielectric loss.

Generally, the single crystal SiC material is known as a semiconductor; the energy gap is about 3 eV and the dielectric constant is about 6.5~10. On the other hand, it is known that the polycrystal SiC material has larger

values for ϵ' and ϵ'' than the single crystal one. Especially, the dielectric response of SiC-B to the RF frequency shows the typical Debye-type relaxation (will be described in the next section). Those differences between the single crystal and the polycrystal SiC materials suggest a certain mechanism determining the dielectric characteristics of the polycrystal SiC.

In 1980's, some researchers at Hitachi Ltd. investigated the properties of a SiC material having a large electrical resistivity (above $10^{11} \Omega m$). The SiC material was made by hot-pressing with BeO addition. They found that the SiC material has the polycrystal structure with electrically conductive grains and non-conductive grain boundaries [5]. The dielectric properties were examined using specimens with various electric carrier concentrations in the grain, prepared by doping alumina. They also analyzed the measured dielectric properties by using two-layer model based on the polycrystal structure [6], [7].

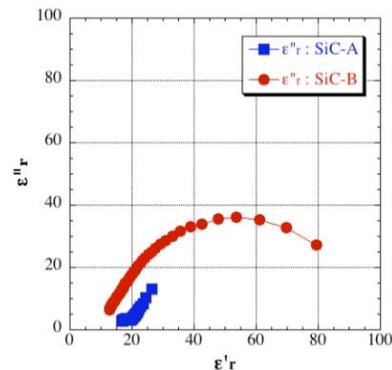


Figure 2: Cole-Cole plots of SiC-A and SiC-B.

PERMITTIVITIES OF SiC CERAMICS

Measurement of permittivity

With use of a dielectric probe kit (HP85070B), we measured the complex permittivities of the SiC-A and SiC-B in the frequency range of 0.2-10 GHz and the temperature range of 300-350 K. Figure 1 shows the measurement results at the room temperature, where the permittivities are plotted as a function of frequency. The responses of ϵ'_r and ϵ''_r for SiC-B show the typical dielectric relaxation below 10 GHz. Figure 2 shows the Cole-Cole plots for SiC-A and SiC-B. The locus of SiC-B was a half circle approximately. Therefore, the dielectric relaxation of SiC-B is Debye-type and can be expressed as follows:

$$\epsilon_r(\omega) = \epsilon_{r\infty} + (\epsilon_{r0} - \epsilon_{r\infty}) / (1 + j\omega\tau), \quad (1)$$

where, $\epsilon_{r0} = \epsilon'_r(\omega=0)$, $\epsilon_{r\infty} = \epsilon'_r(\omega=\infty)$, and τ is the relaxation time. The Debye model is determined by three parameters of ϵ_{r0} , $\epsilon_{r\infty}$ and τ . The measured data of SiC-B

were fitted to the Debye model expressed by Eq. 1, and the three parameters were determined. As seen from Fig. 3, the fitting indicated by the dotted curves shows a good agreement with the measured data.

The Cole-Cole plot of SiC-A shows some signs of the dielectric relaxation at lower frequencies. Recently, we have measured the permittivity of SiC-A in a lower frequency range of 2-1000 MHz, using an impedance material analyzer (E4991A), and confirmed a distinguished curve showing the dielectric relaxation (see Fig. 4).

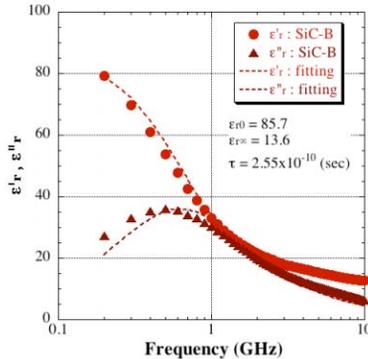


Figure 3: Measured data for SiC-B are fitted with the dielectric relaxation curves based on the Debye model.

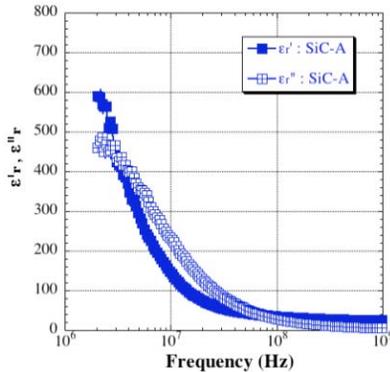


Figure 4: Measured data for SiC-A in the lower frequency range shows the dielectric relaxation.

Two-layer Model

Figure 5 shows a simplified model (referred as two-layer model) representing the polycrystal structure of the hot-pressed SiC ceramics with BeO addition, together with its equivalent circuit [6], [7]. The grain is a p-type semiconductor material with a low resistivity (estimated less than $10^{-1} \Omega\text{m}$). The values of R_g and C_g correspond to the grain property. There is a depletion layer of electric charge carriers next to the grain boundary, which is the origin of the large resistivity of the SiC in spite of the low resistivity inside the grain. The values of C_d and R_d are related to the depletion layer. When boron or aluminium are added instead of BeO, the grain resistivity is affected by the carrier concentration: $\rho(\text{Al}) < \rho(\text{B}) < \rho(\text{BeO})$ according to Ref. [8].

Since SiC-B has a relatively high resistivity (about $2 \times 10^3 \Omega\text{m}$) and boron is used for the densification in the

sintering process, SiC-B is expected to have a similar polycrystal structure. Applying the two-layer model to SiC-B, the effective permittivity can be expressed by the following equations,

$$\epsilon'_r = \epsilon_{r\infty} + (\epsilon_{r0} - \epsilon_{r\infty}) / (1 + \omega^2 \tau^2), \quad (2-a)$$

$$\epsilon''_r = (\epsilon_{r0} - \epsilon_{r\infty}) \omega \tau / (1 + \omega^2 \tau^2) + \sigma / (\epsilon_0 \omega), \quad (2-b)$$

$$\tau = R_g R_d (C_g + C_d) / (R_g + R_d), \quad (2-c)$$

where $\epsilon_{r0} = \epsilon_r'(\omega=0) = (\sigma/\epsilon_0)(\tau_g + \tau_d - \tau)$, $\epsilon_{r\infty} = \epsilon_r'(\omega=\infty) = (\sigma/\epsilon_0)(\tau_g \tau_d / \tau) = (\epsilon_0 (C_g^{-1} + C_d^{-1}))^{-1}$, and $\sigma = (R_g + R_d)^{-1}$ with $\tau_g = R_g C_g$, $\tau_d = R_d C_d$. We assume $d=1 \text{ m}$ and $A=1 \text{ m}^2$ in the model in Fig. 5. Since $R_g \ll R_d$ for SiC-B, $\tau = R_g (C_g + C_d)$ and $\epsilon_{r0} = C_d/\epsilon_0$. Since $\sigma/(\epsilon_0 \omega) < 0.05$ above 0.2 GHz, the second term of Eq. 2-b can be neglected, and then Eq. 2-a and Eq. 2-b express the Debye model. Therefore, the Debye-type relaxation curve of SiC-B can be explained by the two-layer model. Using the three parameters of $\epsilon_{r0} = 85.7$, $\epsilon_{r\infty} = 13.6$, and $\tau = 2.55 \times 10^{-10}$ sec, obtained for SiC-B from the fitting in Fig. 3, the value of R_g is calculated as $R_g = \tau/(C_g + C_d) = 2.8 \times 10^{-1} \Omega$. This value of R_g satisfies the condition of $R_g \ll R_d$, but it is larger than the estimated value less than $10^{-1} \Omega$.

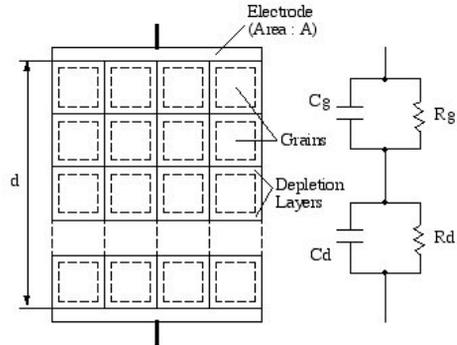


Figure 5: Two-layer model of the hot pressed SiC ceramics with BeO addition, and its equivalent circuit.

We are planning to measure the permittivity of SiC-B in the low frequency range of 1-200 MHz using the impedance material analyzer to obtain further information. We expect that the same model can be applied to SiC-A, showing a similar dielectric relaxation curve.

Temperature Dependence of Relaxation Curve

Figure 6 shows the temperature dependence of the dielectric relaxation curve of SiC-B. The relaxation frequency, $f_r = (2\pi\tau)^{-1}$, where ϵ''_r becomes maximum, becomes higher as the temperature increases. Figure 7 shows the temperature dependence of the parameters for the Debye model, obtained by fitting the measured data. When the temperature rises by 50 K, $\epsilon_{r\infty}$ remains almost constant and ϵ_{r0} increases by 20% while τ greatly decreases by a factor of 1/3.

Now, we will try to analyze these behaviours using the two-layer model. The value of τ is the function of R_g , C_g and C_d . Since the variations of $\epsilon_{r\infty}$ and ϵ_{r0} are much smaller compared with that of τ , the temperature change largely affects R_g . The value of R_g depends on the

mobility of the carrier and the carrier concentration in the grain. Energy levels of impurities in 6H-SiC (a typical polytype of α -type SiC) are: Nitrogen; 0.05-0.24 eV, Aluminium; 0.19-0.49 eV and Boron; 0.3-0.723 eV [9]. These elements are contained in the additives usually used for the densification purpose. When the acceptor (or donor) level is about 0.3 eV in the grain, the temperature dependence of the carrier concentration in grain may be in the freeze-out range at room temperature, because the value of kT (k : Boltzmann's constant, T : absolute temperature) corresponds to 0.026 eV at 300 K. We assume that the temperature dependence of the carrier concentration is in the freeze-out range, and can be simply expressed by $\exp(-\Delta E/2kT)$, where ΔE is energy level of the impurity. Then, R_g is mainly affected by the carrier concentration and τ changes as $\exp(\Delta E/2kT)$. The solid curve in the Fig.7, obtained by fitting with a function of $\exp(\Delta E/2kT)$, shows good agreement with the data of τ . The energy level of $\Delta E = 0.36$ eV was also obtained by the fitting and it was consistent to those of Al and B(boron), which work as acceptors.

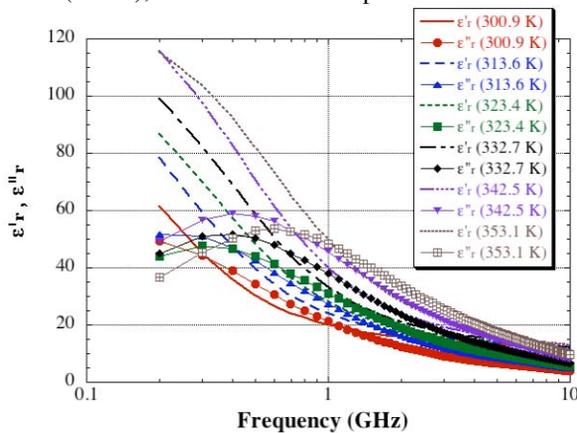


Figure 6: Temperature dependence of the relaxation curve of SiC-B.

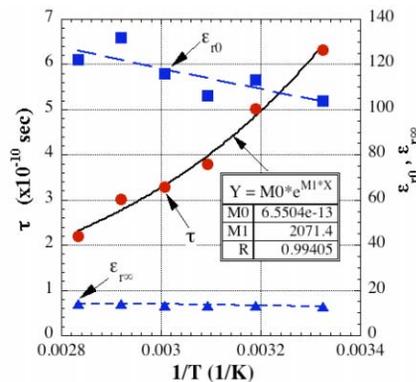


Figure 7: ϵ_{r0} , $\epsilon_{r\infty}$ and τ vs. temperature (SiC-B). The relaxation time, τ decreases abruptly as the temperature increases.

The temperature dependence of the permittivity of SiC-B can be explained by the change of the relaxation time mainly, and largely affected by the carrier concentration in the grain.

Application to Design of HOM Absorbers

When we use SiC ceramics like SiC-B for the HOM absorbers, we should select the material that has suitable values of ϵ_{r0} , $\epsilon_{r\infty}$ and τ . Especially, the relaxation time τ is the most important, because it determines the frequency response of the permittivity. It should be also noted that τ is subject to the temperature. If the frequencies of HOMs are near the relaxation frequency f_r , larger ϵ'_r and ϵ''_r can be used, but the permittivity might depend largely on the temperature. The abrupt increase of ϵ'_r due to the temperature rise is not suitable for high power absorbers, because ϵ'_r affects the electric field of the propagating mode, and it might result in the case of the absorber partly overheated in the worst case. A part of the absorber that is far from the cooling-water circuit (for example the nosecone part of the bullet-shaped absorber) should be carefully designed.

CONCLUSION

Two products of the α -type SiC ceramics are used for the HOM absorbers in the KEKB ARES cavity. Their dielectric responses to the RF frequency show the dielectric relaxation properties. Those properties can be explained by the polycrystal structure model with electrically conductive grains and non-conductive grain boundaries. This model can be a guideline to control the dielectric properties of SiC ceramics, especially for the application to HOM absorbers. We think considering the polycrystal structure is essential to deal with the SiC ceramics as the dielectrically lossy materials.

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