Electromagnetic shielding measurements of CVD Graphene by using KEC and ASTM methods

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Abstract We measured the electromagnetic interference (EMI) shielding effectiveness (SE) of the graphene/PET film. From 1 MHz to 1 GHz, the KEC method was used, and the SE of the graphene film was more than 80 dB at 1 MHz and was decreased in proportion to the frequency. From 5.5 to 10 GHz, the ASTM method was used, and the SE was more than 25 dB and was roughly constant over the measured frequencies. We analyzed the relationship between the measured SEs and the characteristics of a material under test and a fixture for both methods, and clarified the origin of different dependences of SEs on the frequency.

Keyword Electromagnetic shielding, KEC method, ASTM method, CVD graphene

1. INTRODUCTION

With a growth of a wide range of applications of electromagnetic waves, electromagnetic shielding materials used for avoiding the interference problem are becoming increasingly important. For some applications like portable electric devises such as smartphones, shielding materials should be thin and lightweight. Carbon nanomaterials such as graphene and carbon nanotube are potential candidates for thin-conductive films used for the electromagnetic shielding application due to their high electrical conductivity.

The performance of a shielding material is expressed by the electromagnetic interference (EMI) shielding effectiveness (SE), but measurement methods for SE have not been standardized, and the comparability of measurement results by different methods has not been sufficiently considered. In this paper, we measured the SE of the graphene/PET film by using the KEC (1 MHz – 1 GHz) and ASTM (5.5 – 10 GHz) methods. The SEs derived from both methods are differently dependent on the frequency, and we clarified the origin of the different behaviors by analyzing the relationships between measured SEs and the characteristics of a material under test and a fixture.

2. METHOD

2.1. Samples under test

The graphene/PET film is prepared by chemical vapor deposition (CVD) [1]. About 60 layers of graphene are stacked on the 188-μm thick PET substrate, so the thickness of graphene is about 20 nm. The sheet resistance is measured by a four probe method, and is about 9 Ω. The graphene/PET film is a transparent sample as shown in Fig. 1(a).

To compare with the graphene/PET film, we also measure a conventional transparent conductive film made of indium tin oxide (ITO). The thickness of ITO film is roughly the same as the graphene/PET film (~ 188 μm).

2.2. KEC method

The SE from 1 MHz to 1 GHz is measured by using the KEC method [2]. The KEC method is a measuring instrument of the SE in the near field developed by Kansai Electronic Industry Development Center. The instrument for electric SE measurement used in the KEC method consists of symmetrical halves of a TEM cell holding a sample in a gap of a center conductor, as shown in Fig. 1(b) and 2(a). Transmittance between two antennas without a sample (S_{21}^{empty}) and that when a sample is inserted (S_{21}^{mat}) are measured, and the SE is calculated by the following equation:

$$\mathrm{SE} = -20\log\left|S_{21}^{mat}/S_{21}^{empty}\right|. \qquad (1)$$

2.3. ASTM method

The SE from 5.5 to 10 GHz is measured by using the ASTM method [3]. A sample is held between two coaxial-to-waveguide adapters. In this study, we use adapters connecting between a 7-mm coaxial line and a WR-137 waveguide used for C-band as shown in Fig. 1(c). Transmittances with and without a sample are measured, and the SE is calculated by Eq. (1).

3. RESULTS

The SEs of the graphene/PET and ITO films measured from 1 MHz to 1 GHz by the KEC method

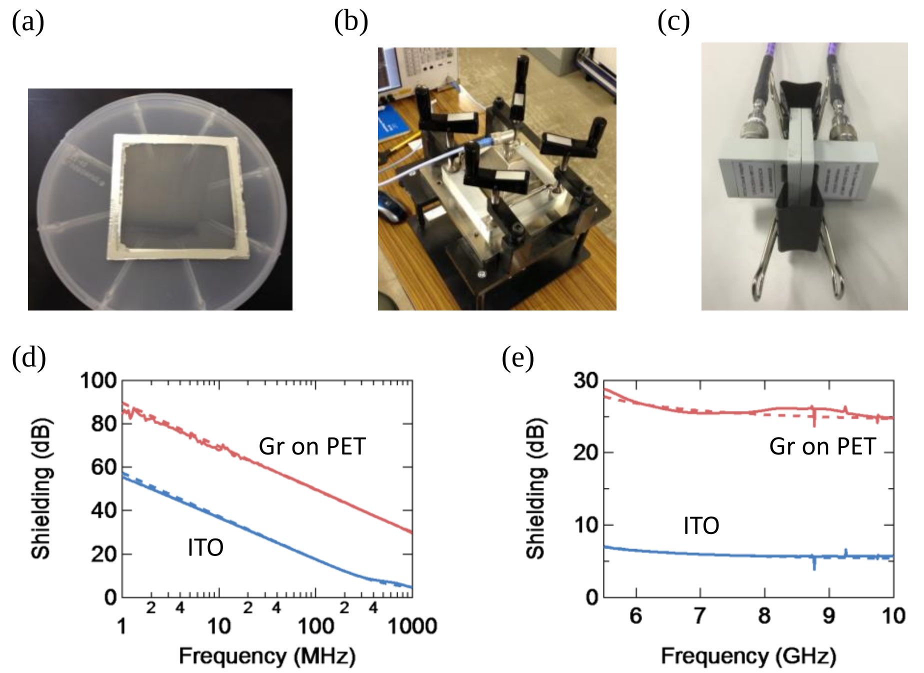

Fig.1. Photo of (a) a graphene/PET film, (b) a test fixture of the KEC method, and (c) a test fixture of the ASTM method. Measurement results (solid line) and fitting lines (dashed line) of the SEs obtained from (d) the KEC method and (e) ASTM method for the graphene/PET and ITO films.

are shown in Fig. 1(d). We can see the SE of graphene/PET film is considerably higher than that of ITO film, and the SE of graphene/PET film is more than 80 dB at 1 MHz, however, the SEs of both samples are decreased in proportion to the frequency.

The SEs of two samples measured from 5.5 to 10 GHz are shown in Fig. 1(e). We can confirm the superiority of the graphene/PET film over ITO film. The SEs of both samples are roughly constant over the measured frequencies, although they are slightly decreased with increasing the frequency.

From Fig. 1(d) and 1(e), we can see the SEs of the same sample obtained from the KEC and ASTM methods are significantly different. In the next section, we clarified that this difference is not resulted from the frequency dependence of the material property, but caused by the different structures of text fixtures used in both methods, by analyzing the relationships between SEs and the characteristics of a material and a fixture.

4. DISCUSSION

4.1. KEC method

Matsubara *et al*. proposed the equivalent lumped element circuits for the KEC electric SE test fixture [4]. Dashed traces in Fig. 1(d) are fitting lines derived from the analysis using the proposed equivalent circuits.

The equivalent circuit without a sample in a fixture is shown in Fig. 2(b), where C_1 is the capacitance of a TEM cell, and C_2 is the capacitance due to the gap of a center conductor. The normalized Z-parameters of this circuit are given by

$$z = \begin{pmatrix} z_{11} & z_{21} \\ z_{12} & z_{22} \end{pmatrix},$$

$$= \frac{1}{j\omega Z_0 C_1 (C_1 + 2C_2)} \begin{pmatrix} C_1 + C_2 & C_2 \\ C_2 & C_1 + C_2 \end{pmatrix}, \qquad (2)$$

where Z_0 is the characteristic impedance of the input/output (in this study, 50 Ω). Then, the transmittance S_{21}^{empty} is written by

$$S_{21}^{empty} = \frac{2z_{21}}{(z_{11}+1)(z_{22}+1) - z_{12}z_{21}},$$

$$= \frac{2j\omega Z_0 (C_1^2 + 2C_1C_2)C_2}{\{C_1 + C_2 + j\omega Z_0 (C_1^2 + 2C_1C_2)\}^2 - C_2^2}, \qquad (3)$$

where ω is the angular frequency. Considering the low-frequency and low-capacitance limits: $\omega Z_0 C_1 \ll 1$, $\omega Z_0 C_2 \ll 1$, which are satisfied for the fixture and measurement conditions in this study, Eq.(3) is reduced to

$$S_{21}^{empty} \simeq 2j\omega Z_0 C_2. \qquad (4)$$

The equivalent circuit when a sample is inserted in a fixture is shown in Fig. 2(c), where R_s is the sheet resistance of a sample, and α is the unknown constant reflecting the geometric structure of a fixture.

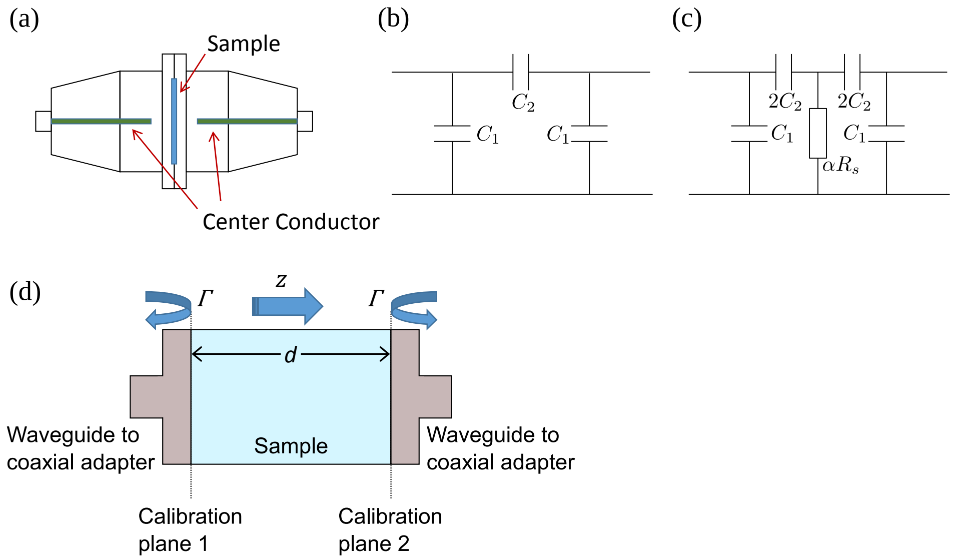

Fig.2. **(a)** Schematic drawing of a test fixture of the KEC method. Equivalent lumped element circuits for the KEC electric SE test fixture (b) without a sample in a fixture and (c) when a sample is inserted in a fixture. (d) Schematic drawing of a test fixture of the ASTM method.

Because a sample divides the gap of a center conductor into two halves, C_2 in Fig. 2(b) becomes two $2C_2$ in series in Fig. 2(c). If we assume $\omega\alpha R_s C_1 \ll 1$ and $\omega\alpha R_s C_2 \ll 1$, then the normalized Z-parameters of the circuit are given by

$$z \simeq -\frac{1}{\omega Z_0 (C_1+2C_2)^2}\begin{pmatrix} j(C_1+2C_2) & -4\omega\alpha R_s C_2^2 \\ -4\omega\alpha R_s C_2^2 & j(C_1+2C_2) \end{pmatrix}. \qquad (5)$$

Then, the transmittance S_{21}^{mat} is written by

$$S_{21}^{mat} \simeq \frac{\dfrac{8\alpha R_s C_2^2}{Z_0(C_1+2C_2)^2}}{\left(\dfrac{1}{j\omega Z_0(C_1+2C_2)}+1\right)^2 - \left\{\dfrac{4\alpha R_s C_2^2}{Z_0(C_1+2C_2)^2}\right\}^2}. \qquad (6)$$

If we further assume $\omega Z_0 C_1 \ll 1$ and $\omega Z_0 C_2 \ll 1$, then Eq. (6) is reduced to

$$S_{21}^{mat} \simeq -8\omega^2 Z_0 \alpha R_s C_2^2. \qquad (7)$$

Therefore, the SE measured by the KEC method is given by the following equation:

$$\mathrm{SE} \simeq -20\log(4\omega\alpha R_s C_2), \qquad (8)$$

so the SE in the linear unit is decreased in proportion to the frequency in the KEC method. Note that this dependence is not resulted from the property of a sample under test, but from the structure of a test fixture.

4.2. ASTM method

In this section, we analyze the SE measured by the ASTM method by using the transmission line theory, see Fig. 2(d). Dashed traces in Fig. 1(e) are fitting lines derived from the analysis.

We assume the conductivity of a sample is sufficiently high, so the imaginary part of the permittivity $\epsilon_r'' \gg 1$. In that case, the reflection coefficient at a sample interface Γ is given by

$$\Gamma = \frac{\gamma_0-\gamma}{\gamma_0+\gamma} \simeq -1 + 2\gamma_0/\gamma, \qquad (9)$$

where γ_0 and γ are the propagation constants of the air region and the material region, respectively, and $|\gamma_0/\gamma| \ll 1$ because $\epsilon_r'' \gg 1$. Then, S_{21}^{mat} is written by

$$S_{21}^{mat} = \frac{z(1-\Gamma^2)}{1-\Gamma^2 z^2},$$

$$\simeq \frac{4z\gamma_0/\gamma}{1-(1-4\gamma_0/\gamma)z^2}. \qquad (10)$$

where $z = \exp(-\gamma d)$ and d is the thickness of a sample.

Considering an extremely thin film, we assume $|\gamma d| \ll 1$, then $z \simeq 1-\gamma d$, and Eq. (10) is reduced to

$$S_{21}^{mat} \simeq \frac{2\gamma_0}{2\gamma_0+\gamma^2 d}. \qquad (11)$$

We assume $\epsilon_r'' \gg \epsilon_r'$ and $\epsilon_r'' \gg (\omega_c/\omega)^2$, where ϵ_r' is the real part of the permittivity of a sample, and ω_c is the cutoff frequency of a waveguide fixture. Then,

$$\gamma^2 d \simeq \frac{\omega^2}{c^2} j\epsilon_r'' d. \qquad (12)$$

where c is the speed of light. For a material with the sheet resistance R_s,

$$\epsilon_r'' = 1/R_s d\omega\epsilon_0, \qquad (13)$$

so Eq. (12) becomes

$$\gamma^2 d \simeq \frac{j\omega}{c^2 R_s \epsilon_0}. \qquad (14)$$

where ϵ_0 is the permittivity of free space. Then Eq.

(11) becomes

$$S_{21}^{mat} \simeq \frac{2\sqrt{\epsilon_a - \left(\frac{\omega_c}{\omega}\right)^2}}{2\sqrt{\epsilon_a - \left(\frac{\omega_c}{\omega}\right)^2} + \frac{1}{R_s c\epsilon_0}}. \qquad (15)$$

For a high conductive material, $1/R_s c\epsilon_0 \gg 1$, then Eq. (15) is reduced to

$$S_{21}^{mat} \simeq 2R_s c\epsilon_0\sqrt{\epsilon_a - \left(\frac{\omega_c}{\omega}\right)^2}. \qquad (16)$$

Therefore, the SE measured by the ASTM method is given by the following equation:

$$\mathrm{SE} \simeq -20\log\left(2R_s c\epsilon_0\sqrt{\epsilon_a - \left(\frac{\omega_c}{\omega}\right)^2}\right), \qquad (17)$$

so the SE depends not only on the material property (sheet resistance), but also on the structure of a test fixture (cutoff frequency). The SE is slightly decreased with increasing the frequency, but it becomes constant when the frequency is much higher than the cutoff frequency.

5. CONCLUSION

We measured the SE of a transparent conductive sheet made of graphene multi layers stacked on a PET film, and confirmed its superiority over ITO film.

We analyzed two SE measurement methods (the KEC and ASTM methods), and clarified the origin of the different dependence of the measured SEs on the frequency. The SE depends not only on the material property, but also on the structure of a test fixture, so if we measure the same material by using the different method or different fixture, then we should obtain different results. Note that both SEs obtained from the KEC and ASTM methods linearly relates to the conductivity of a sample under test for high conducting materials.

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