Fabrication of Novel Electromagnetic Shielding Sheets Using Carbon-Nanotube-Composite Paper

BoJue Li and Takahide Oya
Graduate School of Engineering, Yokohama National University, Tokiwadai 79-5, Hodogaya-ku, Yokohama 240-8501, Japan

(Received 13 December 2013; Accepted 20 March 2014; Published 24 May 2014)

We propose a new electromagnetic shielding (EMS) sheet that uses carbon nanotube (CNT)-composite paper. The electromagnetic environment in which electronic devices such as mobile phones and personal computers operate has become increasingly complex due to increased electromagnetic noise. This noise can cause unexpected behavior in electronic devices. Therefore, EMS sheets are required to shield devices from this noise. Carbon-nanotube composite paper has high electrical conductivity despite being a paper and does not deteriorate like metallic materials which are commonly used for EMS sheets. In this study, we aim to use CNT-composite paper to develop new EMS sheets that have a high shielding effectiveness (SE) (over 30 dB) at frequencies in the 0.1 MHz to 1 GHz range. To achieve this, we made test samples and measured their SE with the Kansai Electronic Industry Development Center (KEC) method. The first CNT-composite paper we developed achieved an SE of 20-50 dB from 0.1 MHz to 100 MHz. However, the SE was 16 dB in the GHz band. To increase the SE in this band, we designed and simulated many different shapes of shielding sheet which we then fabricated to measure their SE. We obtained positive results, indicating that a new shielding paper shape has a higher SE in the GHz band.

[DOI: 10.1380/ejssnt.2014.242]

Keywords: Carbon; Carbon nanotube; Conductivity; Carbon nanotube composite papers; Electromagnetic shielding sheets; Dome-shaped shield

I. INTRODUCTION

With the rapid development of information technology, the electromagnetic environment in which electrical equipment and devices such as mobile phones and personal computers operate has become increasingly complex due to increased electromagnetic noise. This noise can cause unexpected behavior in electronic devices, a phenomenon called electromagnetic interference. The electromagnetic waves emitted by electronic devices can also reveal sensitive information about the device to the environment, termed electromagnetic information leakage. To solve the problems of electromagnetic interference and information leakage, needless electromagnetic wave emissions must be decreased. Metallic electromagnetic shielding (EMS) sheets are commonly used to solve these problems [1–3]. For practical use, a shielding effectiveness (SE) of over 30 dB at a range of frequencies is required.

However, these EMS materials are typically heavy, expensive, and suffer corrosion. Therefore, a new material is needed to overcome these problems. The candidate new material we have focused on is a carbon-nanotube (CNT)-composite paper. The CNT-composite paper [4], combining pulp (paper fibers) and CNTs, has many advantages over metal. For example, this CNT-composite paper has high electrical conductivity despite being paper, is light, is easy to handle, and does not corrode easily because of its unique properties imparted by both the CNTs and the pulp. This CNT-composite paper can be manufactured easily by a simple method based on a traditional technique for making Japanese washi paper [4]. A sample of the CNT-composite paper is shown in Fig. 1. The fabricated sample was about 11 × 9 cm in area and 100 μm thick.

There are three general mechanisms for EMS: reflection, absorption, and multiple-reflection, as shown in Fig. 2 [5–7]. The first mechanism, reflection, is an important mechanism for EMS. To shield electromagnetic waves, mobile charge carriers electrons are needed [5–
The second mechanism, absorption, is also an important factor in shielding electromagnetic waves. The effectiveness of absorption depends on the thickness of the shielding material [8]. The third mechanism, multiple-reflection, can typically be ignored if the shielding material is thicker than the skin depth (the skin effect is the tendency of electromagnetic fields to be attenuated rapidly with depth inside a conductor, the level of which this happens to is called the “skin depth”). Carbon nanotube-composite paper reflects electromagnetic waves and absorbs those not reflected as heat energy on the surface of the paper. It is also a highly conductive material expected to have many mobile charge carriers, and is a highly dielectric material that can efficiently convert incident electromagnetic energy into heat energy. Our CNT-composite paper can also shield electromagnetic waves with the multiple-reflection mechanism. Previously, we have developed and tested CNT-composite paper samples that achieve a high SE (over 30 dB) at frequencies in the 0.1 MHz to 100 MHz range [9, 10]. However, the SE in the GHz band was only 16 dB. To increase the SE in the GHz band, the new research discussed in this paper (the second step of our study) involved designing and simulating many shapes of shielding sheet.

II. DESIGN, FABRICATION, AND EVALUATION METHODS OF NEW SHIELDS

In this study, our final goal was to develop an EMS sheet that had a high SE (over 30 dB), at frequencies in the 0.1 MHz to 1 GHz range using CNT-composite paper up to 500 μm thick. For efficient study, the EMS sheet was first simulated before being fabricated. In the following subsections, our simulation and experimental methods are described. We used an electromagnetic source in both simulation and experimental method for easy evaluation.

A. Simulation Method

For our simulation, we used the finite-difference time-domain (FDTD) method often used for electromagnetic modeling. The absorbing boundary conditions were applied for the FDTD simulation. The simulation software MESH 6.5 (Field Precision, LLC) was used to simulate the electromagnetic environment and design a new EMS sheet. Figure 3 illustrates the result of a simple simulation of the CNT-composite paper when exposed to 500 MHz electromagnetic waves. The square at the bottom of Fig. 3 represents the electromagnetic source. The horizontal bar in the middle of Fig. 3 represents the 200-μm thick CNT-composite paper simulated. Most of the incident electromagnetic waves are clearly shielded by the CNT-composite paper. In Fig. 3, the electric fields are concentrated in the paper and they are described as a black rectangular in the center of the paper. The results of this simulation indicated that our sample paper should perform well. Figure 3 shows an example of schematic of the FDTD simulation result, and the space between the source and the paper we simulated was as the same distance as the measuring instruments.

Figure 4 shows the SE of the simulated samples measured with the KEC method [11] (details of the KEC method are explained in subsection II.B). The results revealed that the CNT-composite paper’s percentage by weight of pulp is an important factor affecting SE. To achieve a higher SE, more CNTs should be used. At frequencies in the 0.1 MHz to 100 MHz range, our sample had an SE of over 30 dB. However, the SE in the GHz band was 16 dB [9], which is not satisfactory.

Ideally, the SE needs to be over 30dB. We designed and simulated an originally shaped shielding sheet that we call a “dome-shaped” shielding sheet (Fig. 5). As the shape of the sheet greatly influences the SE [8], we designed a two-layered shielding sheet with four dome-shaped structures. In the center of the sheet we added another smaller dome-shaped structure to efficiently shield the area which experiences the most powerful electromagnetic waves.

B. Experimental Method

Based on our previously produced paper, we designed many new shapes of shielding sheet [9, 10]. The next step
of this study was to fabricate the dome-shaped shielding sheet with the following experimental method. The dome-shaped shielding sheet consists of a two-layered shielding sheet, four dome-shaped structures, and one smaller dome-shaped structure under the two-layered sheet, as shown in Fig. 5. Figure 6 shows the fabrication method [4]: (1) Preparation of pulp materials. (2) Preparation of pulp dispersion by adding pulp to water. (3) Preparation of CNT materials. (4) Preparation of CNT dispersion. Dispersion of CNTs and TritonX-100 in water by irradiating with ultrasonic waves for 30 minutes. (5) Mixing the dispersions from steps (2) and (4). (6) Scooping up paper fiber and CNTs with a net from the step (5) dispersion. (7) Drying to solidify the composite paper. To fabricate the paper, we used 120 mg of CNTs (NC7000, Nanocyl), 1 g of pulp, and 120 mg of TritonX-100 for dispersion. We used TritonX-100 instead of sodium dodecyl sulfate (SDS), which was used in our previously study [10], because TritonX-100 has a better dispersing ability [12]. The fabricated sample was about 11 × 9 cm² in area and 100 μm thick. The practical dome-shaped structure can be made from the sheet paper. Before drying the composite paper to complete making, we set 1 mm diameter of five metal wires at intervals of 1 cm on the stage of a heating press firstly, and then we put our paper on them. Finally, we press and dry our paper by the press.

Figure 7 shows the fabricated dome-shaped shielding sheet sample. We confirmed that there were five dome-shaped structures in the center of the paper. Moreover, using the same method, we fabricated another type of EMS based on the dome-shaped shielding sheet: Figure 8 describes the structure of an advanced version of dome-shaped shielding sheet. The five dome-shaped structures were located side-by-side in the center of the two-layer sheet. Both dome-shaped samples were about 11 × 9 cm in area and 300-μm thick.

In this study, we used the KEC method [11], which assesses the SE of both electric and magnetic fields, to test the fabricated sample. The SE can be calculated with the formula below, while Fig. 9 shows the simple measuring instrument used (on the basis of on the transmission level when the test sample is not in the measuring instrument, the SE can be measured as the insertion loss.

\[
\text{SE(dB)} = 20 \log \frac{E_1}{E_2}
\]

Here, \(E_1\): the receivable level when the test sample is not in the measuring instrument. \(E_2\): the receivable level when the test sample is in the measuring instrument.

**III. SIMULATION RESULTS**

Figure 10 shows the simulated results of the SE in an electric field for the previously designed samples [9] and the newly designed dome-shaped samples. The new dome-shaped shielding sheet has an obviously higher SE than the previous one-, two, and three-layered CNT-composite shielding sheets at frequencies in the 0.1 MHz to 1 GHz range. Moreover, the dome-shaped shielding
Figure 10: Simulated electric field SE of previously designed one- and two- and three-layered shielding sheets and newly designed dome-shaped shielding sheet.

Figure 11: Previously designed samples.

Previous-A

Previous-B

Previous-C

Figure 12: Simulated electric field SE of previously designed angularly structured shielding sheets and newly designed dome-shaped shielding sheet.

Figure 13: Measured electric field SE for previously designed one-layered CNT sheet and newly designed dome-shaped sample.

FIG. 10: Simulated electric field SE of previously designed one- and two- and three-layered shielding sheets and newly designed dome-shaped shielding sheet.

FIG. 11: Previously designed samples.

sheet achieved an SE of 23 dB in the GHz band, which was better than the previously designed samples. We also confirmed that the dome-shaped structure showed a better SE than three layered shielding sheets paper. So we considered the shape of the shielding sheet was also an important factor.

Figure 11 shows our previously designed samples constructed with both flat and zigzag-shaped shielding sheets [9, 10]. We also compared our dome-shaped shielding sheet with these previously designed samples. Figure 12 shows the electric field SE of the previously and newly designed samples. We confirmed that even the “Previous-A”, “Previous-B”, and “Previous-C” samples had a higher SE (over 16 dB) in the GHz band than a flat sheet-shaped shield. Moreover, we also confirmed that the dome-shaped shield had a higher SE than all of them.

It was important that the dome-shaped shielding sheet could reflect the electromagnetic wave efficiently through the simulations of SE in electric fields as shown in both Figs. 10 and 12. It is important to note that the unique structure and large surface of the dome-shaped shielding sheet had a higher reflecting effect than the previous samples. The electromagnetic waves were not only reflected by each dome-shaped structure, but also reflected around the dome-shaped structures. This combination of dome-shaped structures produces a higher SE.

IV. EXPERIMENTAL RESULTS

From the simulation results, we confirmed that our newly designed dome-shaped shielding sheet would achieve a higher SE than previous samples. Furthermore, the large surface area of the dome-shaped shielding sheet gave us new ideas on how to make new EMS sheets. We fabricated a one-layered CNT-composite paper, a dome-shaped shielding sheet, and an advanced dome-shaped shielding sheet. The SE of the three samples was measured with the KEC method.

Figure 13 shows the electric field SE for the one-layered CNT-composite sheet and the dome-shaped shielding sheet. By comparing the results, it can be concluded that the dome-shaped shielding sheet achieves a high SE at frequencies in the 0.1 MHz to 100 MHz range, also achieving an SE of 27 dB in the GHz band, which was higher than our previous samples. It was important that the large surface of the dome-shaped shielding sheet could reflect the electromagnetic wave efficiently and achieve a higher SE. Therefore, our dome-shaped shielding sheet performed better than our previous samples.

Figure 14 describes the electric field SE of the dome-shaped shielding sheet and the advanced version of the dome-shaped shielding sheet (Fig. 8). The advanced dome-shaped shielding sheet achieved an SE of 30 dB in the GHz band, which was better than our previous samples. The advanced dome-shaped shielding sheet achieved a higher reflection and multiple-reflection effectiveness in the GHz band. A broad peak can be seen between 100 MHz and 1 GHz (Fig. 8). This suggests the existence...
of resonance, which is expected in case of highly conductive composites as the skin effect becomes significant [13].

V. CONCLUSIONS

We aimed to develop a new EMS sheet that had a high SE (over 30 dB) at frequencies in the 0.1 MHz to 1 GHz range by using CNT-composite paper up to 500 μm thick. First, we used simulation software to design a uniquely shaped shielding sheet that we named “dome-shaped.” Second, we compared our dome-shaped shielding sheet with our previous shielding sheets. Surprisingly, this dome-shaped shielding sheet achieved an SE of 23 dB in the 1 GHz band, which was better than the 16 dB achieved by our previously designed shielding sheets. Third, we fabricated our dome-shaped shielding sheet. It achieved an SE of 27 dB in the GHz band, higher than our previously fabricated samples. We also fabricated an advanced version of the dome-shaped shielding sheet which achieved an SE of 30 dB in the GHz band.

In conclusion, our CNT-composite papers achieved a high SE at frequencies in the 0.1 MHz to 1 GHz range. Moreover, simulated results revealed that surface area was an important factor in achieving a high SE. The large surface area of the dome-shaped shielding sheet could reflect the electromagnetic waves more efficiently and achieve a higher SE. The experimental results supported our simulation results, and the advanced version of the dome-shaped shielding sheet achieved a high SE in the GHz band, high enough for practical use. However, the advanced version of the dome-shaped shielding sheet was only tested experimentally (Fig. 14). In the next stage of our research, we will simulate our advanced dome-shaped shielding sheet.

In this study, we observed SE peaks in both simulated and measured results. In addition, we found the different trends between simulated and measured results, i.e., SE peak was at 1 MHz in simulation and at 10 MHz in measurement. In general, the SE that is calculated by higher-degree equation is estimated as functions of wavelength of electromagnetic waves, conductivity, dielectric constant, permeability, and the thickness of the shield. That means a general shielding sheet has a peak of SE that can be controlled by such parameters. In addition, our shield was made as a paper, so that the surface shape was complex and different from simulated one strictly. From the simulated and experimental results, we considered the complex surface shape was also important to shield. In simulations, we used the measured parameters in experiments. However, we have not succeeded to estimate the values of permeability and dielectric constant because of measuring difficulties, and make clear the inside structure of the CNT composite paper so far. So we must overcome these problems and estimate the parameters to simulate samples accurately in future work. We will fabricate a new shielding sheet based on the dome-shaped CNT-composite paper with an improved shielding effectiveness.

Acknowledgments

This work was partly supported by a Grant-in-Aid for Scientific Research on Innovative Areas (No. 25110015) from Japan Society for the Promotion of Science (JSPS). The authors are grateful to Mr. Kazuki Komiya of the Electronic Semiconductor Technology Group at Tokyo Metropolitan Industrial Technology Research Institute for his support on the KEC measurements and the members of the research and development laboratory at KJ Special Paper Co., Ltd. for their supports.