Твердотельная электроника

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Yuriy Didenko, **Dmitry Tatarchuk**, Ph.D., **Iryna Patsora**, **Ievgen Kharabet**, **Anton Franchuk**
National Technical University of Ukraine «Kyiv Polytechnic Institute»,
st. Polytechnique, 16, Kyiv, 03056, Ukraine.

The specific conductivity of metal-polymer composites in the microwave range

The specific conductivity dependence of the metal-polymer composites on dispersed phase volume part in the frequency range 8...12 GHz are investigated. The models of the specific conductivity structure dependence based on equations of Maxwell-Garnett and Nielsen are obtained. The comparison of the models was performed. Results of the numerical modeling and experimental data are shown. References 3, figures 3.

Keywords: *composite, specific conductivity, microwave range, dielectric permittivity, dielectric loses.*

Introduction

Currently, electronic systems are increasingly used in various fields of human activity. This leads to an increase in the quality requirements of the electronic devices. Particular attention is paid to reliability, noise immunity, reduce of the mutual influence of electronic devices and blocks. Moreover environmental protection from electromagnetic radiation is becoming increasingly important nowadays. Many different methods were developed for solving these problems. However, one of the most effective among them is shielding. In accordance to this developing of the protective coating systems based on the composite metal-polymer materials seems to be promising line of research.

Composite materials based on fine-dispersed metal particles are of great interest for experimental and theoretical studies. The physical properties of such materials are radically different from the properties of continuous medium, made from the same materials. Selection of the optimal ratio between the components provides composite materials with the desired magnetic, dielectric, radio absorbing and other special properties. However, to date, these materials are studied insufficiently, which limits their effective use. That’s why the aim of this work is to study the specific conductivity of metal-polymer composites in the microwave range.

The specific conductivity of the metal-polymer composites

It is known that there is a direct relation between the specific conductivity of material (σ) and its loss coefficient (ε''), which is described by the formula:

$$\sigma = 2\pi f \varepsilon_0 \varepsilon'' , \qquad (1)$$

where f is the frequency, ε_0 is the dielectric permittivity of the vacuum, and ε'' is the imaginary part of the relative dielectric permittivity of material. Therefore, knowing the complex dielectric permittivity of the material allows calculating its specific conductivity.

There are many equations that allow the calculation of the complex dielectric permittivity of a composite material if dielectric constants of its components and their volume parts are known. The most known and used among them are the Maxwell-Garnett (2), the Lichtenecker (3) and Nielsen equations (4) [1, 3].

$$\varepsilon_c = \frac{(1-q)\varepsilon_m + q\beta\varepsilon_d}{1-q+q\beta} , \qquad (2)$$

$$\varepsilon_c = \varepsilon_m^{1-q} \varepsilon_d^{q} , \qquad (3)$$

where ε_c, ε_m, ε_d are dielectric permittivities of composite, matrix material and metal dispersed phase respectively, q is the volume part of dispersed phase, β is the form factor (for spherical particles $\beta = 3\varepsilon_m / (\varepsilon_d + 2\varepsilon_m)$).

$$\varepsilon_c = \varepsilon_m \frac{1 + A \cdot B \cdot q}{1 - B \cdot \Psi \cdot q} , \qquad (4)$$

where $B = \frac{\varepsilon_d / \varepsilon_m - 1}{\varepsilon_d / \varepsilon_m + A}$, $\Psi = 1 + \frac{1-q_m}{q_m^2} q$, A is the form factor which can take values from 1,5 (for spherical particles) to 4 (for scale-shaped particles), q_m is the maximum possible volume part of the dispersed phase.

The complex dielectric permittivity of the dispersed metal phase can be determined from the expression:

$$\varepsilon_d = 1 - \frac{\omega_p^2}{\omega\left(\omega + \frac{i}{\tau}\right)}, \qquad (5)$$

where $\omega = 2\pi f$ is the cyclic (angular) frequency, ω_p is the plasma frequency, τ is the relaxation time.

The relaxation time can be defined as:

$$\tau = \frac{\sigma_d}{\omega_p^2 \varepsilon_0}, \qquad (6)$$

where σ_d is the specific conductivity of dispersed phase material (metal).

Models of composite material's conductivity based on the expressions 1,2,4 - 6 were obtained. Lihtenecker's equation was not considered because it is intended for the case when the properties of the matrix material and the dispersed phase differ little.

Experimental results

Results of calculation were compared with experimental data to verify obtained models and to select the most appropriate one. Simulation and experimental investigation were conducted in the frequency range of 8-12 GHz.

The composite materials were prepared by electromechanical mixing of the dispersed phase with the matrix material at room temperature. Obtained material was shaped in form of rectangular samples whose dimensions were specifically chosen so they completely fill the cross-section of the waveguide. The sample's thickness was 2 mm. Polymer with complex dielectric permittivity $\varepsilon = 2{,}73 - j0{,}2$ was used as the matrix material. Aluminum and copper powder with a particle size of 0,06 – 0,2 µm were used as disperse phase.

Dielectric constants were measured with implementation of the method of the reflection-transmission [2]. Measurements of reflection (S_{11}-parameter) and transmission (S_{21}-parameter) coefficients of electromagnetic microwave energy radiation were performed using panoramic meter. Then conductivity of the tested samples was calculated and experimental results were processed using least squares method. The theoretical and experimental results are presented in Figures 1 and 2. As seen from these figures, the difference between experimental results and simulation does not exceed 18%.

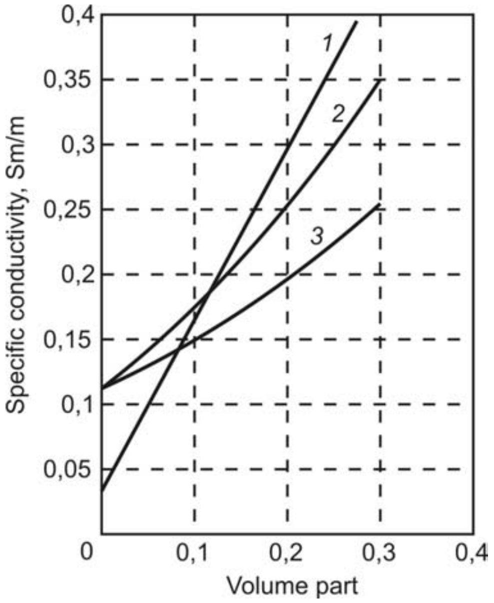

Fig. 1. The specific conductivity of Al-polymer composite: 1 – experimental data; 2 – Nielsen model; 3 – Maxwell-Garnett model

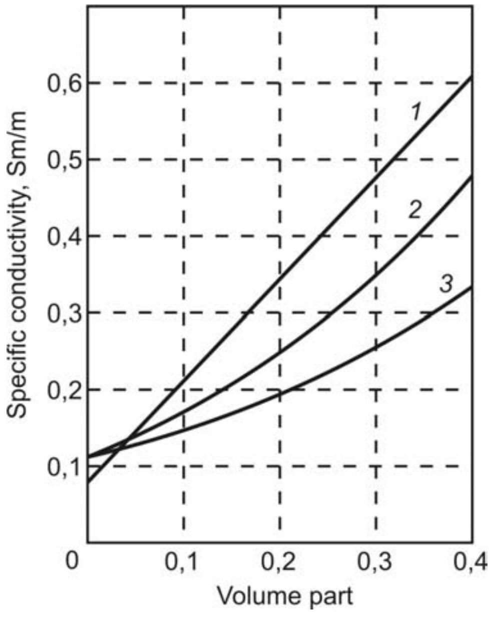

Fig. 2. The specific conductivity of Cu- polymer composite: 1 – experimental data; 2 – Nielsen model; 3 – Maxwell-Garnett model

As could be seen from presented figures, experimental data (Fig. 1, 2, line *1*) agrees better with the numerical results obtained using model, which is based on the Nielsen equation (Fig. 1, 2, line *2*).

In this case the form factor used in the Nielsen formula was equal to 4 which correspond to scale-shaped particles. Such shape of the metallic phase particles is the result of their clumping during mixing, which is confirmed by the electron microscopy results of the material structure studies (Fig. 3).

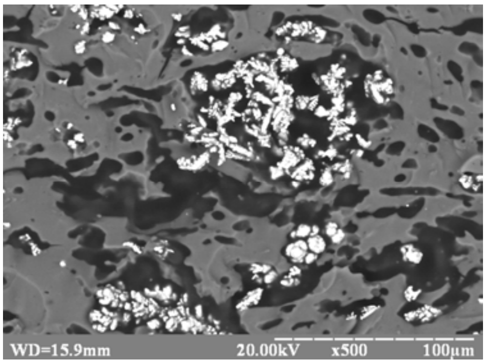

Fig. 3. The structure of metal-polymer composite

Conclusions

- The modeling of the composite's specific conductivity dependence on structure was performed. The models are based on equations of Maxwell-Garnett and Nielsen.
- Model results are in good agreement with experimental data up to the moment when volume part of metal in the composite exceeds 0,4.
- Comparison of experimental and numerical results shows that model based on Nielsen equation provides more accurate results. The difference between experimental results and simulation does not exceed 18%. It indicates this model is applicable for prediction of properties of metal-polymer composite materials.

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Ю.В. Діденко, **Д.Д. Татарчук**, канд.техн.наук, **І.В. Пацьора**, **Є.І. Харабет**, **А.С. Франчук**
Національний технічний університет України «Київський політехнічний інститут»,
вул. Політехнічна, 16, корпус 12, м. Київ, 03056, Україна.

Питома провідність композитів метал-полімер у НВЧ діапазоні

Досліджено залежність питомої провідності композитів метал-полімер від об'ємної частки дисперсної фази в діапазоні частот 8...12 ГГц. На основі рівнянь Максвелла-Гарнетта і Нільсена отримані моделі залежності питомої провідності структури. Виконано порівняння моделей. Наведено результати числового моделювання та експериментальні дані. Бібл. 3, рис. 3.

Ключові слова: *композит, питома провідність, НВЧ діапазон, діелектрична проникність, діелектричні втрати.*

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Ю.В. Диденко, **Д.Д. Татарчук**, канд.тех.наук, **И.В. Пацёра**, **Е.И. Харабет**, **А.С. Франчук**
Национальный технический университет Украины «Киевский политехнический институт»,
ул. Политехническая, 16, корпус 12, г. Киев, 03056, Украина.

Удельная проводимость композитов металл-полимер в СВЧ диапазоне

Исследована зависимость удельной проводимости композитов металл-полимер от объемной доли дисперсной фазы в диапазоне частот 8...12 ГГц. На основе уравнений Максвелла-Гарнетта и Нильсена получены модели зависимости удельной проводимости структуры. Выполнено сравнение моделей. Приведены результаты численного моделирования и экспериментальные данные. Библ . 3, рис. 3.

Ключевые слова: *композит, удельная проводимость, СВЧ діапазон, диэлектрическая проницаемость, диэлектрические потери.*

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