DOI: 10.17725/rensit.2022.14.243

Heating dynamics of metal-dielectric structures with nanometer-thin conductive films under the influence of microwave fields

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Received August 19, 2022, reviewed August 26, 2022, accepted August 31, 2022

Abstract: **The paper presents the results of experimental studies of the heating dynamics of metal-dielectric structures (MDS) with aluminum conductive nanoscale films deposited by magnetron sputtering on low-cost substrates (glass, sitall, PET and PTFE) under exposure to monochromatic ultrahigh frequency (UHF) fields in a waveguide. At film thicknesses less than 2 nm, the experimental samples had mostly dielectric properties. Noticeable interaction of the films with microwave, causing thermal phenomena, was observed at thicknesses greater than 2 nm and reached a maximum at 5 nm. Thermal degradation processes of the metallized layer manifested in different ways in MDS with solid and polymer (flexible) substrates. Breakdown in conductive films generally occurred at temperatures below the melting temperature of the film material and occurred perpendicular to the electric field strength vector.**

Keywords: **metal-dielectric structure, nanometer conductive films, microwave, waveguide, thermal effect, breakdown**

PACS 78.70.Gq

Acknowledgments: The study was supported by a grant from the Russian Science Foundation (Project no. 22-22-20126).

For citation: Vladimir V. Starostenko, Evgeniy V. Grigoriev, Alim S. Mazinov, Sergey P. Arsenichev, Evgeniy P. Taran, Aleksandr V. Starosek, Ibraim Sh. Fitaev. Heating dynamics of metal-dielectric structures with nanometer-thin conductive films under the influence of microwave fields. *RENSIT: Radioelectronics. Nanosystems. Information Technologies,* 2022, 14(3):243-248. DOI: 10.17725/rensit.2022.14.243.

Contents

1. INTRODUCTION

The intensive development of the ultrahigh frequency (UHF) range and the widespread adoption of nanotechnologies in microelectronics made the investigation of the resilience of electronic components to electromagnetic fields (EMF) particularly relevant. Numerous experimental studies conducted by different groups of scientists in various countries [1,2] show that out of the range of such film microstructural components as active devices, dielectric and conductive elements that form the basis of integrated circuits, sensors, microcircuits, electronic modules, etc., the most vulnerable ones are conductive films, primarily the contact sites [1,2].

Studies of the properties of nanometer conducting films are mainly devoted to the research of their electrodynamic (diffraction) properties. In this paper we present the results of the dynamics of electrothermal processes in nanometer conductive films considered in previous works [3–9].

The study of physical phenomena in conductive structures of microelectronic products exposed to EMF is extremely difficult, so studies were conducted on macroobjects with metal-dielectric structures (MDS) of finite dimensions in the waveguide pathway. Conversion of microwave energy into heat energy during exposure of MDS is determined by the thickness and material of the conductive film, the generator power and the amount of absorbed energy (exposure time). All studies were conducted with a natural heat transfer, i.e., without forced dissipation of heat. The work uses the data of linear diffraction on MDS in the waveguide (unchanged values of the standing wave ratio VSWR and attenuation T), theoretical and experimental data on the dynamics of thermal processes in MDS. In experimental studies the effects of film thickness, generator power and exposure time (absorbed energy) on both the heating dynamics and the breakdown (burn-through) of MDS films were determined.

The current trend in electronics is to reduce the geometric dimensions of microstructural elements, which is related to the thicknesses of the films used in them. In conductive nano-scale films, depending on the thickness the transition from dielectric (no film) to mirror (reflective) structure takes place. In this regard, this work focuses on physical phenomena in conductive films with a thickness of 1-10 nm exposed to high-power microwave radiation.

The aim of this paper is to experimentally investigate the processes of conversion of microwave field energy into thermal energy during exposure of metal-dielectric structures with nanometer-thick films.

2. EXPERIMENTAL METHODS

The solid dielectric substrates used were 18×18×0.15 mm cover glasses and sitalloy substrates. Before sputtering, the substrates were plasma polished and had a roughness of no more than 10 nm. In addition, as film substrates, we used polymeric PET (lavsan) and PTFE (fluoroplastic) sheets, the surfaces of which are quite different from those of glass and sitallbased substrates [10,11].

The diffraction characteristics were investigated in the waveguide on a panoramic VSWR and attenuation T meter (R2-56, f = 2.9-4.1 GHz). In the microwave range, the ratios between the incident, reflected, transmitted, and absorbed waves do not depend on frequency, since the structural inhomogeneities are much smaller than the wavelength; they also do not change with the scale conservation of the cross-sectional dimension ratios of the MDS and waveguide [10,11].

Schematic diagram of the installation for direct exposure of MDS to monochromatic EMF is shown in **Fig. 1**.

The M105-1 magnetron operating at a frequency of 2450 MHz with an output power of up to 700 W was used as a microwave radiation generator. The waveguide path had dimensions of 34×72 mm. In all waveguide studies, the condition $S_{\mathrm{MDS}} << S_{\mathrm{wg}}$ was met, where S_{MDS} and S_{wg} are the cross sections of MDS and waveguide. It should be noted that

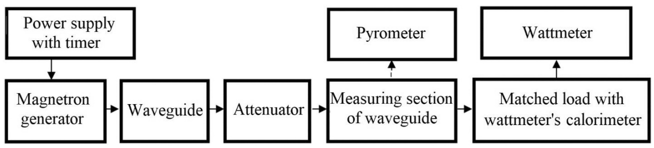

Fig. 1. *The structural diagram of the installation for the study of electro-thermal processes in MDS.*

the VSWR and attenuation T values are the same whether the MDS is located normal or parallel to the vector of the electric component of the H_{10} wave field. We chose an orientation of the MDS relative to the waveguide axis, that was convenient for conducting measurements.

During electrothermal exposure, the studied sample was placed in the measuring section of the waveguide path, and after dosed exposure to microwave radiation (multiple of 1 *s*), the temperature of the sample was measured with a MEGEON 16350 pyrometer through a special aperture in the waveguide. Then, the sample was allowed to cool down to ambient temperature and the process was repeated with a different generator power. Since significant errors are possible in temperature measurements, we conducted five cycles of experiments with subsequent averaging of the obtained values.

3. ELECTRODYNAMIC AND THERMAL EXPERIMENTAL STUDIES

In panoramic measurements of diffraction characteristics on objects in a waveguide, the VSWR characterizes the reflected wave by field, and the transmittance (attenuation) by power. Most often relative powers of reflected (R), transmitted (T) and absorbed (A) waves are used as diffraction characteristics – optical coefficients. Condition $R + T + A = 1$ follows from power balance, where R, T and A are normalized to input power diffraction characteristics; R is calculated through VSW, T is power transmittance (attenuation), absorption A is from power balance [10,11].

The most interesting is the behavior of R, T, and A in the thickness range from 1 to 10 nm. At such thicknesses the maximum possible conversion of EMF energy to thermal energy occurs. When using budget substrates and film deposition methods, the notion of thickness up to 7...10 nm is rather conventional. This is due to the roughness of the surface, on the one hand, and spatial and ohmic inhomogeneity of the film, on the other. At such thicknesses the film is inhomogeneous and has an island structure (a set of scattering centers, nanoparticles, etc. [12]). Usually, for such film thicknesses, the sputtering time correlation is used.

Temperature dependences of MDS on the thickness of deposited aluminum film at the same exposure time $t = 1$ *s* for microwave radiation power of 15, 30 and 60 *W* are shown in **Fig. 2**.

It follows from Fig. 2 that up to film thicknesses $d = 2$ nm MDS is more of a dielectric. At higher values of film thickness ohmic losses begin to appear. More detailed dynamics of EMF energy conversion to heat at $1.5 < d < 3$ nm are presented in the inset of Fig. 2. Up to thicknesses of $d = 2$ nm the film temperature is equal to ambient temperature, at $d > 2$ nm the film temperature increases due to ohmic losses, reaching maximum values at $d \approx 5$ nm. At $d > 5$ nm the film is practically formed. Reflection rather than absorption is predominant in this case. In general, at $d > 10$ nm a stationary relation between reflected

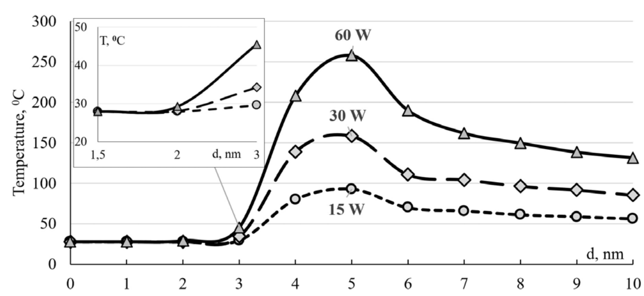

Fig. 2. *Temperature dependences of MDS on thickness of Al film at t = 1 s at generator power of 15, 30 and 60 W.*

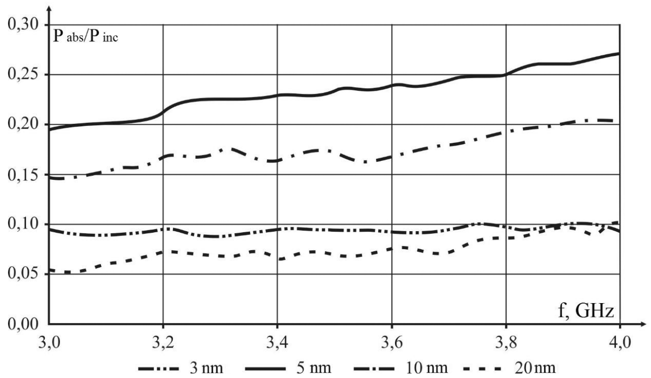

Fig. 3. *Dynamics of the P_{abs}/P_{inc} frequency dependence in working range of R2-56 for MDS with aluminum films of different thicknesses.*

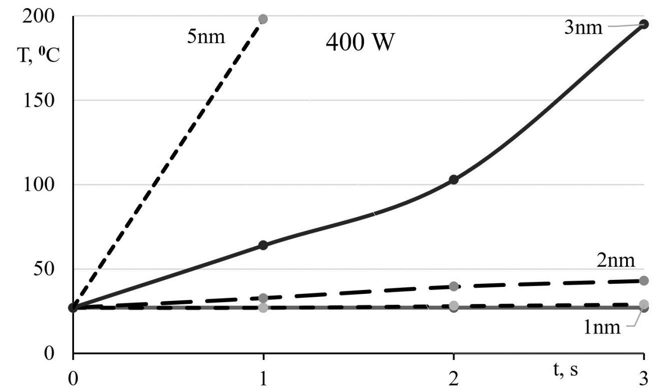

Fig. 4. *Temperature dependences of MDS with films of 1, 2, 3 and 5 nm thickness exposed to 400 W EMF.*

and passed waves is established, the absorbed power is determined by the incident power.

Fig. 3 shows the dependences P_{abs}/P_{ins} for MDS with films of different thicknesses in the frequency range of the panoramic meter P2-56. These dependencies show that the maximum conversion of EMF energy to thermal energy occurs at film thicknesses near 5 nm. Similar results are obtained for MDS with films with specific conductivity more than 10^7 Sm/m, in particular, with films of gold, aluminum, etc. [5,12]. The insignificant dependence of P_{abs}/P_{ins} on the frequency (Fig. 3) is explained by the change of the electrical dimensions of MDS in the frequency range of the panoramic gauge. Comparison of the dependencies shown in Fig. 2 and 3 indicates that, at the values of generator power indicated in Fig. 2, only about 30% of the incident power is converted into heat (Fig. 3).

With an increase in generator power, it is possible to heat the film to the melting temperature (**Fig. 4**). As follows from Fig. 4, noticeable conversion of EMF energy into heat begins at film thicknesses of 3 nm or more. In an MDS with a film thickness of 3 nm, the temperature rose to 200°C in 3 *s* (Fig. 4). MDS with film thickness of 5 nm experienced breakdown in 1 s, similar situation takes place for MDS with film thickness of 7 and 10 nm.

In MDS at catastrophic failure the film temperature may not reach the melting temperature – when exposed to EMF the film breakdown occurs earlier. This is due to the specifics of current and temperature distribution in the objects of finite size when exposed to EMF. Maximum values of the electric component of the field are produced on the edges parallel to the *E*-component of the EMF. The electrons' drift to the edges of the EMF is due to the Lorentz force, consequently, this leads to large current densities and thermal gradients on the edges of the EMF parallel to the *E*-component of the field. All this is the cause of the breakdown, which develops perpendicular to the *E*-component of the field.

Fig. 5 shows typical examples of breakdown in MDS on solid and polymer substrates.

Thermal changes in MDS with polymer substrates are observed as early as at film thicknesses of 2 nm: MDSs thus change their

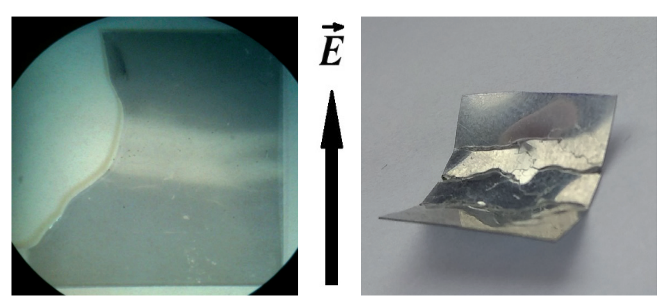

Fig. 5. *Breakdowns and fractures in MDS on solid and polymer substrates, film thickness 10 nm, P = 60 W, t = 2 s.*

geometry, the substrates begin to bend and twist.

4. CONCLUSION

The paper presents the results of studies of electrothermal processes in conducting films less than 10 nm thick when exposed to EMF in a waveguide. Noticeable temperature phenomena appear in conductive films at thicknesses greater than 2 nm, and thermal processes appear differently in MDS with solid and polymer (flexible) substrates. Breakdown in conductive films usually occurs at temperatures below the melting temperature of the film material and occurs perpendicular to the vector of the electric field component.

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