1. INTRODUCTION

Transmission of high-power microwave radiation through dielectric windows in vacuum devices is a challenging problem in many fields of science and technology. Dielectric windows are widely used in high-power microwave oscillators and amplifiers, space and ground-based communication systems, technological devices for production of new materials, and systems for plasma heating in magnetic confinement devices. At high microwave intensities, various types of microwave discharge can develop on the output and input dielectric windows. The discharges absorb microwave radiation, distort the transmitted signals, and lead to the heating of the window surface and the subsequent failure of the window [1].

An important stage of a microwave discharge on a dielectric is the so-called electron multipactor [2, 3]. The multipactor discharge is a result of an electron avalanche caused by secondary electron emission (SEE) from metal and dielectric surfaces bombarded by the electrons oscillating in the microwave field. Multipactor discharges developing on the surfaces of dielectric windows in waveguide and quasi-optical microwave systems are usually referred to as single-sided multiplicators (in contrast to two-sided multiplicators developing between the metal walls of a waveguide or a microwave cavity; see, e.g., [2–5]).

The bombardment of the dielectric by the electrons generated in a single-sided multipactor leads to the heating of a thin (~1 μm) surface layer of the dielectric. High temperature gradients (≥10⁴ K/cm) arising in this layer result in the appearance of microcracks on the dielectric surface. The multipactor can also initiate the development of a surface microwave breakdown due to either ionization of the residual gas near the dielectric surface [6] or a short-term increase in the conductivity of the dielectric surface caused by the accumulation of point defects of the crystal lattice (color centers) under electron bombardment in the discharge [7–10].

In the classical single-sided multipactor on a dielectric [3], the external microwave electric field is directed along the dielectric surface (Fig. 1) and the emitted electrons return back to the surface under the action of the restoring force \( F_z \), caused by the positive charge accumulated on the dielectric (or the ponderomotive force if the amplitude of the microwave field is nonuniform along the normal to the dielectric surface [11]). For this type of discharge to develop, it is necessary that the electron oscillation energy in the microwave field \( \epsilon_{osc} = \left( \frac{eE_0}{\omega} \right)^2/2m_e \) (where \( E_0 \) is the amplitude of the external microwave electric field; \( \omega \) is the microwave circular frequency; and \( e \) and \( m_e \) are the charge and mass of an electron, respectively) be higher.
than the first crossover energy $\varepsilon_1$ (the energy above which the secondary emission yield (SEY) $\delta$ is larger than unity).

The multipactor on a dielectric surface is a combination of rather complicated processes, which require thorough theoretical analysis and computer simulations. In particular, study of microwave power absorption by a multipactor discharge is of considerable interest.

In [12], the following estimate for the coefficient of microwave power absorption by a single-sided multipactor on a dielectric was obtained: $\kappa = W_{\text{abs}}/W_{\text{inc}} \approx 0.004 T_e^{3/2}$, where $W_{\text{abs}}$ is the power absorbed per unit area of the dielectric surface, $W_{\text{inc}} = cE_0^2/8\pi$ is the power flux density of the incident microwave radiation, and $T_e$ is the temperature (in eV) of secondary electrons emitted from the dielectric surface. According to this estimate, for typical values of $T_e$ at a level of 1–2 eV, the power absorbed by the multipactor discharge comprises about 1% of the incident microwave power. Nearly the same estimate of the absorption coefficient (~1%) was obtained in [13] in analyzing the effects related to the electron space charge in a single-sided multipactor. In spite of such a low absorption coefficient, the absolute value of the power surface density released on the surfaces of dielectric windows in modern high-power microwave sources ($W_{\text{inc}} \sim 1$ kW/cm$^2$) can be quite sufficient to cause inadmissible thermal and mechanical stresses in the surface layer of the dielectric, resulting in the appearance of microcracks on the window surfaces.

Particle-in-cell (PIC) simulations of a single-sided multipactor [14] showed that the absorption coefficient slightly increased with microwave intensity. Thus, as the electron oscillation energy was raised by two orders of magnitude (from $\approx 200$ eV to $\approx 20$ keV), the absorption coefficients increased only fourfold (from 0.5 to 2%).

It should be noted that, in [12–14], the reason for the gradual increase in the coefficient of microwave power absorption by a single-sided multipactor with increasing microwave power was not discussed and, accordingly, no analytical expression describing such an increase was derived.

The objective of the present study was to analyze the processes resulting in an increase in the coefficient of microwave power absorption by a single-sided multipactor in a strong microwave field. For this purpose, it was necessary to solve the following problems:

(i) to derive an analytical formula describing the dependence of the coefficient of microwave power absorption by a single-sided multipactor on the incident microwave power;

(ii) to develop a PIC code for simulation of a single-sided multipactor with allowance for the electron space charge, the finite temperature of emitted electrons, and elastic and inelastic reflections of electrons from the dielectric surface;

(iii) to numerically simulate a single-sided multipactor and study how electron reflections and the shape of the energy dependence of the SEY affect the coefficient of microwave power absorption;

(iv) to perform experimental measurements of the coefficient of microwave power absorption by a multipactor discharge developing on the surface of a dielectric (quartz) plate placed in a waveguide and compare the experimental data with the results of theoretical analysis and computer simulations.

2. SECONDARY ELECTRON YIELD

In analyzing the multipactor discharge, it is important to adequately choose the dependence of the SEY $\delta(\varepsilon, \theta)$ on the energy and incidence angle of a primary electron. At present, in theoretical studies on multipactor discharges, the SEY is customarily described by Vaughan’s empirical formula [15],

$$\delta = \delta_m(V_{\theta - m}^{1-V})^k,$$

where $V = (\varepsilon - \varepsilon_0)/(\varepsilon_m - \varepsilon_0)$; $\varepsilon$ is the energy of an incident (primary) electron; $\varepsilon_0$ is the cutoff energy, below which $\delta$ is zero; $\delta_m = \delta_m(1 + \theta^2/2\pi)$ is the peak value of $\delta$ at a given angle of incidence $\theta$ of a primary electron (counted from the normal to the surface); $\varepsilon_m = \varepsilon_m(1 + \theta^2/\pi)$ is the energy corresponding to the peak value of $\delta$ at $\theta = 0$; $\varepsilon_m$ is the peak value of $\delta$ at $\theta = 0$; and $\varepsilon_m$ is the energy corresponding to the peak value of $\delta$ at $\theta = 0$.

The energy dependence described by formula (1) is shown by curve I in Fig. 2.

In theoretical and numerical studies of multipactor discharges (see, e.g., [12–14, 16, 17]), the simplified Vaughan’s formula with a zero cutoff energy $\varepsilon_0 = 0$ (Fig. 2, curve 2) is widely used.

![Image](image_url)