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LOW-TEMPERATURE PLASMA

Long-Lived Plasmoids Generated by Surface Microwave Discharges in Chemically Active Gases

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Abstract—The generation of long-lived microplasmoids is observed during the irradiation of a metal–dielectric surface with a high-power microwave beam in a chemically active gas mixture ($H_2 + O_2$; $CH_4 + O_2$). The lifetime of these plasmoids substantially exceeds the characteristic recombination and cooling times of plasmoids arising at the target surface in a chemically inactive medium. © *2005 Pleiades Publishing, Inc.*

1. INTRODUCTION

Plasmoids with an abnormally long decay time (long-lived plasmoids) have been observed in laser sparks [1, 2], microwave discharges [3, 4], high-current arcs [5, 6], etc. Long-lived plasmoids generated under laboratory conditions have attracted interest primarily in connection with attempts to model such an interesting (but poorly understood) phenomenon as ball lightning [7, 8].

Long-lived plasmoids generated by high-current multispark gliding surface discharges were first observed and described in [9]. It was shown that, regardless of the composition of the ambient gas, a gliding surface discharge excited along a multielectrode metal–dielectric system generates thermally equilibrium plasmoids whose decay time is much longer than the characteristic recombination time. When such plasmoids are injected into a chemically inactive gas (argon, nitrogen, air, etc.), their lifetime is determined by radiative cooling. When plasmoids fall into a chemically active gas (such as a $H_2 : O_2$ or a $CH_4 : O_2$ mixture), their lifetime increases substantially. In [9], this effect was attributed to the influx of chemically active particles that compensate for radiative energy losses. Being sustained by a chemically active medium, the plasmoid in turn affects the medium by activating the gas mixture and promoting its ignition.

In this paper, the possibility is investigated of generating long-lived plasmoids in discharges excited by high-power microwave beams at metal–dielectric surfaces in combustible gas mixtures. This type of discharge was described and studied in [10, 11]. In [12–14], it was shown that, when a dielectric surface interspersed with metal grains was irradiated by a high-power microwave beam, multiple sparks (microplasmoids) were generated at the interfaces between the metal grains and the dielectric. The main goal of the present study is to find out whether the surface microplasmoids produced in a chemically active medium may give rise to long-lived plasmoids similar to those observed in experiments with high-current multielectrode gliding discharges [9].

2. EXPERIMENTAL SETUP

A schematic of the experimental setup is shown in Fig. 1. Pulsed microwave radiation generated by magnetron *1* is fed through attenuator *2* and circulator *3* to horn–lens antenna *4*. The antenna forms converging microwave beam *12,* which is launched into cylindrical metal chamber *5* and then into reactor chamber *9*. The reactor chamber is a preevacuated quartz cell that is filled with a working gas before each particular experiment. The pressure in the metal chamber is atmospheric.

Dielectric target *10* is placed in cell *9* in the focal region of the microwave beam. The target surface exposed to microwave beam *12* contains metal grains ≤1 mm in size (see Fig. 2). The number of grains per unit area of the target surface is chosen such that the target is transparent to low-power microwaves. However,

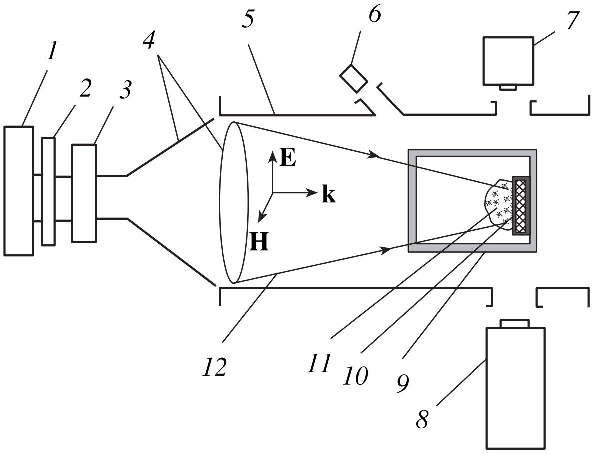

Fig. 1. Scheme of the experiment.

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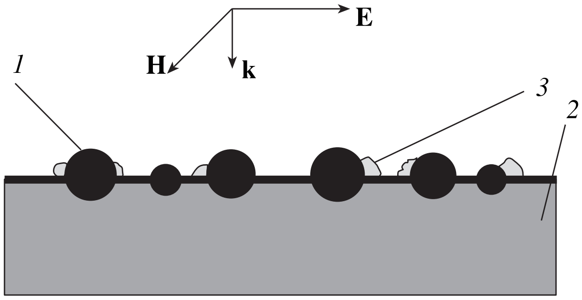

Fig. 2. Sketch of a metal–dielectric target: (*1*) metal grains, (*2*) dielectric substrate, and (*3*) microplasmoids (sparks).

at a microwave intensity of $I \geq 10$–100 W/cm^2, multiple local sparks arise at the interfaces between the metal grains and the dielectric and the transmission coefficient of the target decreases substantially because of microwave absorption by local plasmoids.

The parameters of microwave radiation in our experiments were as follows: the wavelength was $\lambda \cong 2.5$ cm, the pulse duration was $\tau_i \cong 5$–10 μs, and the peak power was $P_i \leq 100$ kW.

The reactor cell was filled with argon or a hydrogen–oxygen ($H_2 : O_2$) or a methane–oxygen ($CH_4 : O_2$) mixture at a pressure of $10 \leq p \leq 200$ torr.

The time evolution of the optical glow from the reactor cell was recorded with the help of FER-7 streak camera *7* (see Fig. 1); KADR-IOFRAN image intensifier *8*, operating in the frame mode (four successive frames with a variable exposure time and variable time delay between them); and collimated photomultiplier *6*.

3. EXPERIMENTAL RESULTS

Figure 3 shows a typical streak image (negative) of the glow from the reactor cell. The slit of the FER-7 streak camera was oriented along the normal to the surface of the metal–dielectric target (along the *z* axis). In this case (see Fig. 4), the radiation was received from the region of width $\Delta x \cong 2.0$ mm and length $\Delta z \cong 4$ cm.

The reactor cell was filled with a $H_2 : O_2$ (180 : 90 torr) mixture. The duration of the microwave pulse was $\tau_i \cong 10$ μs, and the microwave peak power was $P_i \cong 100$ kW.

The target surface is located at $z = 0$, and the microwave pulse is switched on at $t = 0$.

It can be seen from Fig. 3 that local optical bursts arise on the metal–dielectric target irradiated with microwaves. These bursts correspond to microscopic surface discharges developing at the interfaces between the metal grains and the dielectric. The duration of the optical glow from the surface discharges (200–250 μs) substantially exceeds the microwave pulse duration. Periodical pulsations of the glow are observed.

When the cell is filled with a chemically inactive gas (Ar, N_2, O_2, etc.), the glow from surface microscopic discharges (sparks) terminates just after the end of the microwave pulse.

It should be noted that streak images obtained with the help of the FER-7 camera provide information only about a very small region of the metal–dielectric surface. In order to study the formation of microplasmoids beyond the field of view of the FER-7 camera, we carried out experiments with the KADR-IOFRAN image intensifier, operating in the frame mode. This allowed us to obtain a series of four successive photographs of the entire target surface during a microwave pulse. Typical series of photographs taken during a microwave pulse are presented in Fig. 5. The exposure time of each

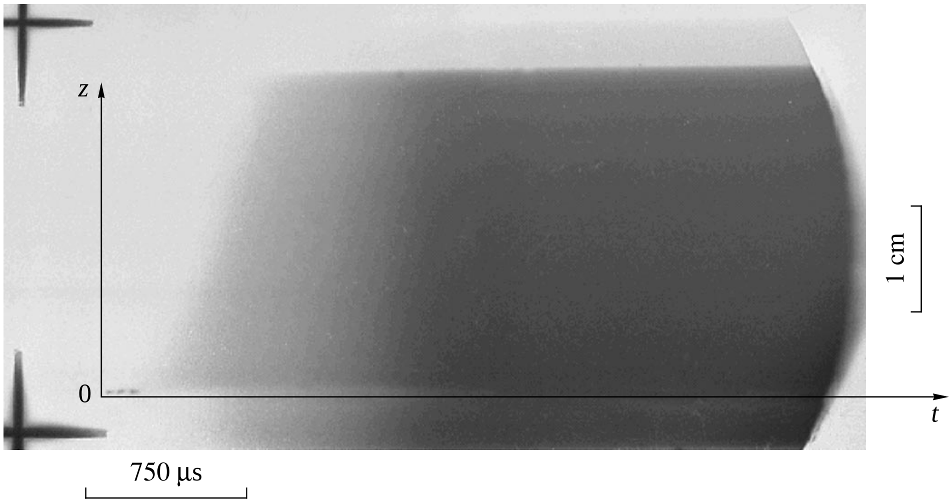

Fig. 3. Typical streak image of the glow from the reactor cell filled with a $H_2 : O_2$ (180 : 90 torr) mixture.

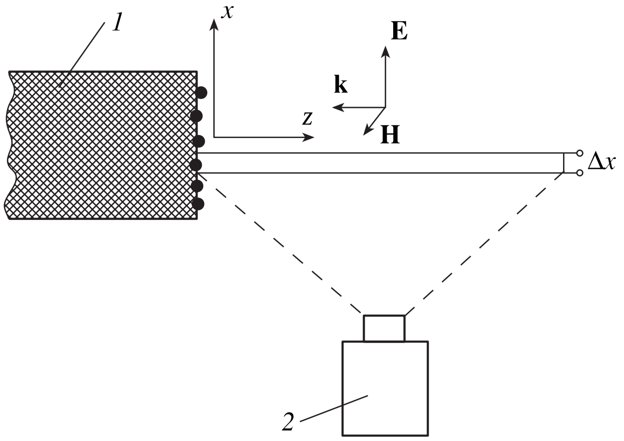

Fig. 4. Scheme of photographing the glow from the reactor cell with the help of an FER-7 streak camera with a slit oriented along the *z* axis.

frame was 30 μs, and the delay time between the frames was 200 μs. The reactor quartz cell was filled with (*1*) a $H_2 : O_2$ (120 : 60 torr) mixture, (*2*) a $CH_4 : O_2$ (45 : 90) mixture, and (*3*) pure oxygen ($p \cong 135$ torr).

It follows from this figure that surface microwave discharges in oxygen decay just after the end of the microwave pulse (Fig. 5a, row *3*). When the reactor cell is filled with a chemically active (combustible) gas mixture (Fig. 5; rows *1*, *2*), the lifetime of microplasmoids increases on average to ~200 μs (Fig. 5b; rows *1*, *2*). However, a few (usually, one or two) microplasmoids continue to glow over a time longer than 600 μs. This effect is most pronounced in a methane–oxygen mixture (Figs. 5c, 5d; row *2*).

Photographs of the glow from a methane–oxygen mixture taken under the same conditions as those in Fig. 5 but at different times with respect to the begin-

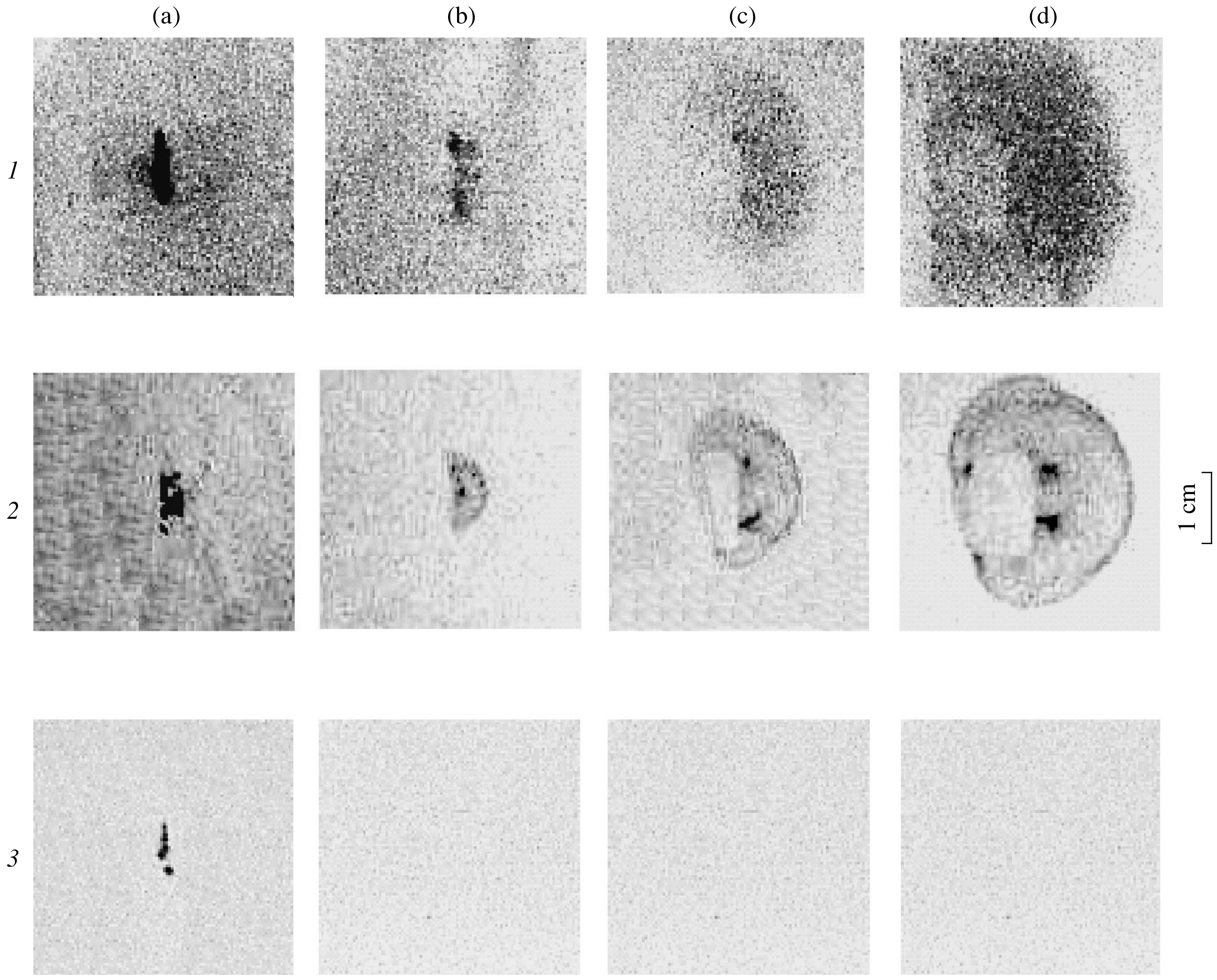

Fig. 5. Typical photographs of the glow from the reactor cell filled with (*1*) a $H_2 : O_2$ (180 : 90 torr) mixture, (*2*) a $CH_4 : O_2$ (45 : 90 torr) mixture, and (*3*) O_2 (135 torr). The exposure time of each frame is 30 μs, and the time delay between the frames is 200 μs.

ning of the microwave pulse showed that long-lived plasmoids existed over 1–1.2 ms, up to the final bright burst occurring over the entire chamber.

In Figs. 3 and 5, one can see quasi-spherical glow waves initiated by surface discharges and identified in [15] as "incomplete-combustion waves."

4. DISCUSSION

Mechanisms for sustaining long-lived plasmoids generated in a chemically active gas mixture by a high-current multispark surface discharge were discussed in [9]. It was suggested that any thermally equilibrium high-temperature plasmoid (regardless of the way in which it was produced) is long-lived if its size is less than a certain critical size: $r_p \leq r_{\mathrm{cr}}$.

A surface microwave discharge at a metal–dielectric target (see Fig. 2) can also be used to produce plasmoids of this kind. Experiments have shown [10, 11] that the irradiation of a metal–dielectric target under conditions such that

$$\Psi\tau_i \geq 0.1\ \mathrm{J/cm^2} \qquad (1)$$

(where Ψ is the microwave intensity in W/cm^2 and τ_i is the microwave pulse duration in seconds) is accompanied by the generation of multiple plasmoids (sparks) at the interfaces between the metal grains and the dielectric.

An analysis of the possible mechanisms for plasma production allowed the authors of [10, 12] to suggest that the observed phenomenon is related to the injection of electrons from the metal to the conduction band of the dielectric at the metal–dielectric interface. The electron emission at the metal–dielectric interface can be substantially intensified due to the following two effects: (i) a decrease in the work function of the metal and (ii) an increase in the microwave electric field at the metal grains.

The injection of electrons into the dielectric increases the conductivity of a narrow dielectric layer adjacent to the metal up to a value typical of semiconductors (see [16]). Microwave absorption in the dielectric layer with the induced conductivity is accompanied by its heating. As the temperature at the metal–dielectric interface grows, both the dielectric conductivity and the electron flux into the dielectric from the metal increase. The resulting thermal instability [16] leads to explosive energy release at the metal–dielectric interface and a solid–plasma phase transition.

This processes may lead to the generation of long-lived plasmoids observed in our experiment. These plasmoids are sustained by the influx of chemically reacting particles from the ambient medium. The plasmoids in turn can influence the medium [9], thus promoting volume combustion in the reactor cell.

Microplasmoids generated by a surface microwave discharge (in contrast to those generated by high-current gliding discharges [9]) do not undergo axial acceleration under the action of electrodynamic forces. As a result, they stay over several milliseconds near the metal–dielectric interface, where they were produced.

5. CONCLUSIONS

Our experiments have shown that microplasmoids arising at metal–dielectric surfaces irradiated by high-power microwave beams in hydrogen–oxygen and methane–oxygen mixtures can evolve into long-lived plasmoids similar to those observed in experiments with high-current multielectrode gliding discharges.

Our experimental results confirm the assumption that long-lived plasmoids can arise when small-size, thermally equilibrium plasmoids with a sufficiently high temperature are somehow produced in a chemically active gas mixture.

In view of these findings, it is expedient to more thoroughly investigate the parameters of long-lived plasmoids and to search for new methods for their excitation, including laser-spark excitation.

It is also of interest to study the problem of utilizing long-lived plasmoids to initiate the combustion of gas mixtures, in particular, in supersonic flows (see [15, 17]).

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