Detachment of a Microwave-Excited Plasmoid From Molten Glass

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***Abstract*—The evolution of a plasmoid (fireball) ejected by localized microwaves from a solid substrate is presented. The plasmoid is first fed by the substrate material (glass in this case) through a plasma column, which is detached from the substrate, and then evolves as a stable fireball buoyant in the air atmosphere. The experimental characterization of these fireballs is presented, and their resemblance to the ball lightning in nature is indicated.**

***Index Terms*—Atmospheric-pressure plasmas, microwave ovens, plasma material processing, plasma sources.**

IN THIS experiment, the fireball (plasmoid) is directly excited from a solid substrate, as in [1]. A molten hot spot is created in the solid substrate in a thermal runaway process [2], which leads to the plasma-column ejection and to the formation of a fireball [see Fig. 1(a)]. This plasmoid then evolves as a self-sustained fireball, and its feeding plasma column is detached from the molten hot spot [see Fig. 1(b)]. A nipple at the bottom of the fireball [see Fig. 1(c)] remains as a trace, which also shows the fluidlike nature of this fireball. The fireball is floating as an elastic jellyfish in the air atmosphere within the microwave cavity, and it stably sustains while radiated by microwaves [see Fig. 1(d)]. These results were obtained in the setup of [1] by a 2.45-GHz 0.8-kW magnetron. The images [see Fig. 1(a)–(d)] were captured in different runs by a Nikon Coolpix E8800 still camera using automatic exposure. They represent a transient evolution in a typical timescale of a few seconds between images.

Following [1], our recent experiments have shown unique features of the fireballs excited by localized microwaves from molten hot spots, which differ them from gaseous spherical microwave discharges. Measurements of the optical emission spectra of these fireballs indicate the dominant presence of solid substrate materials in their content. Depending on the substrate, these fireballs may consist of silicon, sodium, potassium, or even metals such as iron, copper, aluminum, and titanium. Hence, the synthesis of fireballs from liquid or solid substrates (in bulk, grain, or powder form) or their combination is feasible using this technique. The fireballs produced seem denser and heavier than gaseous plasma spheres, and they behave more like dense vapor (almost in liquid state). The fireball motion is attributed to a ponderomotive force due to the gradient in the microwave power along their motion path, but it seems to be also affected by air-pressure gradients, airflow, and gas dynamics. Hence, one may conceive maneuvering these fireballs by various means and even launching them to remote targets. The feature of self-impedance-matching adaptation observed in our preliminary experiments may indicate a tendency to attain a plasma resonance condition (note that a scattering matrix analysis yielded a dielectric permittivity of $\varepsilon_r = -2$ within the fireball [1]). This unique feature of adaptive self-impedance matching makes these fireballs "microwave friendly," and it alleviates their microwave control in practice.

We investigated fireballs *in situ* by small-angle X-ray scattering (SAXS) at the European Synchrotron Radiation Facility and found nanoparticles in the diameter range of ~50 nm within the fireball [3]. Furthermore, we also found that some of the fireball effects observed are not limited to dielectric materials since we managed to directly eject plasma columns from solid copper and other metals, as well by localized microwaves [4]. *In situ* SAXS measurement revealed nanoparticles of ~20- to 100-nm size within the ejected column. Optical spectroscopy confirmed the dominance of copper particles in the plasma column (directly originating from the copper substrate). The spectral analysis also enabled temperature measurement, as described in [4]. Generation of nano- and microparticles of copper was also verified by *ex situ* scanning electron microscopy, demonstrating a direct conversion mechanism of solid metals to nanoparticles.

Laboratory plasmoids (e.g., [5]) resemble the natural ball lightning (BL) phenomenon in nature. The latter have been observed in nature on rare occasions in stormy weather, volcanic activities, and earthquakes. They are described as peculiar luminous bodies floating in the air, bouncing on the ground, rotating as tornados, or even passing through windows. One model [6], [7] suggests that the BL is generated by normal lightning that strikes the ground and evaporates silica and carbon; hence, BL luminosity is maintained by a slow combustion process in which silicon nanoparticles are gradually fused together to form larger silicon spheres with oxidized outer surfaces. This model suggests that reactions such as $SiO_2 + 2C \rightarrow Si + 2CO$ reduces SiO_2 to Si in the form of nanoparticles. The BL is then evolved as an elastic aerogel structure because of mutual electrostatic aggregation of the bipolar-charged nanoparticles. During atmospheric oxidation, silicon dioxide layers grow on the surface of these nanoparticles, hence further reducing air oxygen diffusion to their silicon cores. Our recent experimental study has confirmed the feasibility of this mechanism [8].

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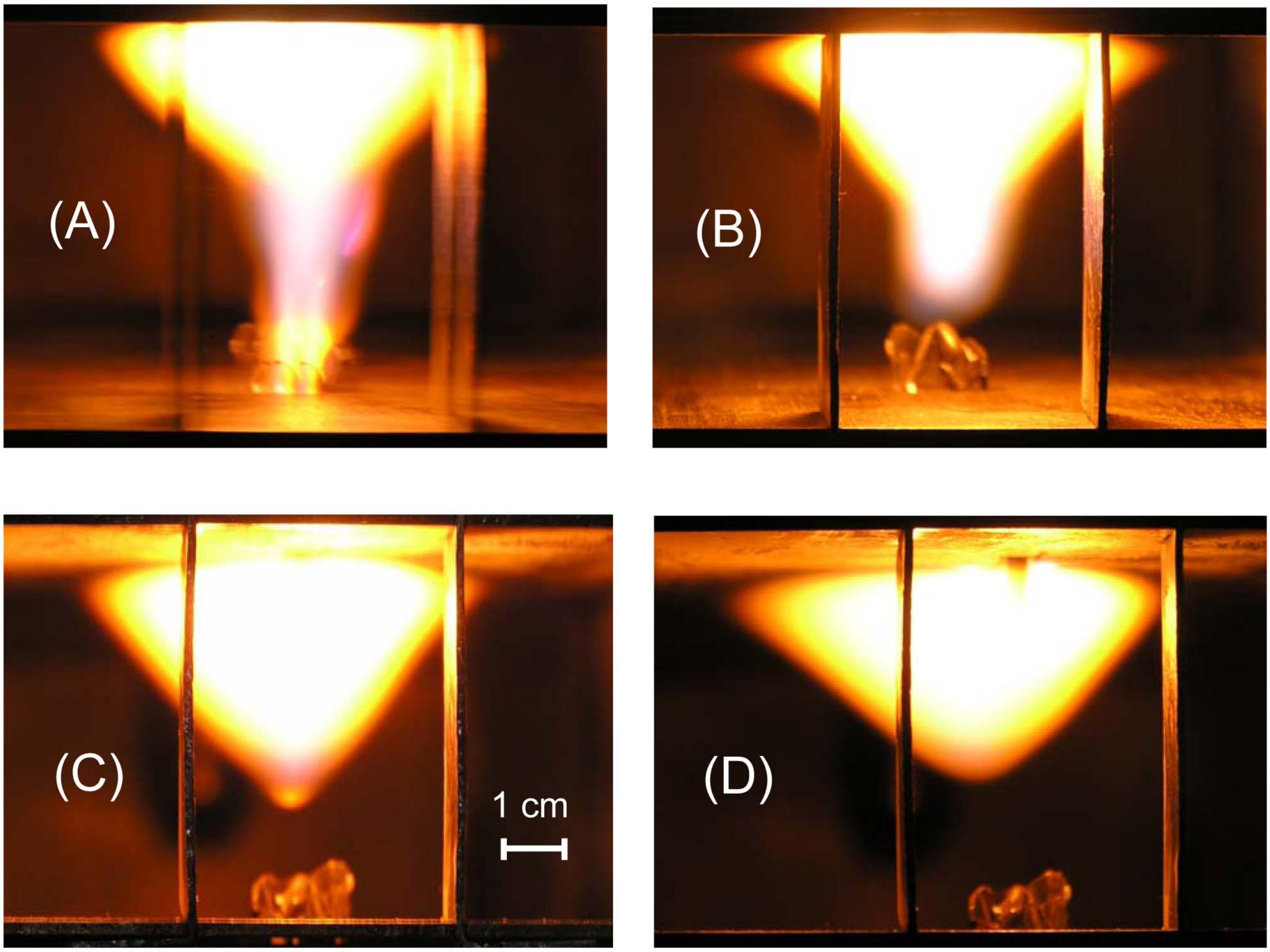

Fig. 1. (a) A hot spot is created by localized microwaves in a glass substrate situated on the bottom of the microwave cavity [1]. A plasma column is ejected from the molten hot spot and forms a fireball (plasmoid). The evolving fireball is fed by the molten hot spot through the plasma column emitted from the glass. (b) The plasma column is detached from the hot spot and lifts up toward the fireball. (c) The plasma column is collected by the fireball via a condensed nipple at its bottom, which shows the fluidlike nature of this plasmoid. (d) A stable fireball buoyant in the air atmosphere while being radiated by microwaves.

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