Fireball Ejection from a Molten Hot Spot to Air by Localized Microwaves

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A phenomenon of fireball ejection from hot spots in solid materials (silicon, germanium, glass, ceramics, basalt, etc.) to the atmosphere is presented. The hot spot is created in the substrate material by the microwave-drill mechanism [Jerby *et al.*, Science **298**, 587 (2002)]. The vaporized drop evolved from the hot spot is blown up, and forms a stable fireball buoyant in the air. The experimental observations of fireball ejection from silicate hot spots are referred to the Abrahamson-Dinniss theory [Nature (London) **403**, 519 (2000)] suggesting a mechanism for ball-lightning initiation in nature. The fireballs observed in our experiments tend to absorb the available microwave power entirely, similarly to the plasmon resonance effect in submicron wavelengths [Nie and Emory, Science **275**, 1102 (1997)].

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Natural ball-lightning phenomena were observed quite rarely in the atmosphere, mostly during thunderstorms, earthquakes, volcanic activities, and tornadoes [1–3]. Ball-lightning effects were observed in various shapes, bouncing on the ground, rotating as tornados, moving against winds, and passing through windows. Abrahamson and Dinniss [4] proposed a model for ball-lightning generation in nature, suggesting that normal lightning striking the ground ejects silicon-dioxide nanoparticle networks to the atmosphere, whereas oxidation provides the internal energy for the ball-lightning evolution and for its self-sustained existence. In most laboratory experiments, however, fireballs were ignited in air by electric breakdown [5] or by electromagnetic (EM) discharges [6–11]. Kapitza produced fireballs by high-power radio waves [6], suggesting accordingly an external-energy mechanism for fireballs in nature. Ohtsuki and Ofuruton [7], and Ofuruton *et al.* [8] obtained fireballs by microwaves in an air-filled cavity, whereas their fireballs exhibited motions similar to those observed in nature (also through ceramic plates and against wind). Fredkin and Mayergoyz [12] proposed recently that an object irradiated by EM waves in plasmon resonance "may visually manifest itself as ball lightning." The plasmon resonance effect may cause also a strong concentration of the EM energy near particles, as observed experimentally in optical wavelengths [13–15]. This effect may decrease the EM power density needed to sustain natural fireballs. Here we introduce experimental observations of fireballs originated from molten hot spots in solid materials (e.g., silicon, glass, germanium, and alumina) rather than by air discharges, and demonstrate conceptually the mechanism proposed by Abrahamson and Dinniss [4] for the origin of ball lightning from silicate substrates in nature.

Fireballs originating from a molten hot spot were observed in our experiments in two distinct modes, namely, spontaneous and stimulated modes. A spontaneous emission of fireballs from liquefied hot spots was observed in our earlier melting experiments of germanium and basalt bulks [16,17]. The microwave furnace was made of a 3/4-liter rectangular cavity, containing a $\sim$20 cm^3 bulk of germanium or basalt, and powered directly by a 2.45 GHz, 0.6 kW magnetron. On several occasions, after a hot spot evolved within the basalt or germanium bulk, a fireball arose and was blown into the air. Then, the fireball moved like an elastic glowing balloon, floating in the air toward the microwave antenna, which was $\sim$0.2 m away, and disappeared. Then, again, another fireball emerged from the hot spot in the bulk, flew at a speed of $\sim$0.2 m/s along the cavity to the antenna, and so on, repeatedly, in a $\sim$1-second lifetime cycle. Many tens of successive fireball ejection cycles were continuously observed in each event, as shown in [18]. However, these spontaneous events occurred quite rarely and unpredictably in the microwave-furnace operations.

Seeking for a consistent method to activate fireballs intentionally from molten hot spots in solid substrates, we found that the microwave-drill technique [19] can be operated reversely as an effective stimulator for fireball ejection. The resulting experimental method for stimulating the fireball ejection from a hot spot is illustrated in Fig. 1. First, the hot spot is created in a thermal-runaway process by the microwave drill on the surface of the silicate substrate. Then, the microwave drill is pulled out slowly from the hot spot, dragging a molten drop out of the substrate material. This drop is vaporized and blown up in a form of a stable fireball floating in the air atmosphere within the microwave cavity.

The experimental setup for stimulated fireball generation from molten hot spots is depicted in Fig. 2. It consists of a rectangular waveguide (8.6×4.3 cm^2 cross section) ended by a mirror made of vanes under cutoff, enabling a direct view into the waveguide, as in [16,17]. This setup differs, however, by the inner microwave drilling bit incorporated within, which creates the hot spot intentionally and stimulates the fireball in a controlled manner. The microwave cavity is energized by a 2.45 GHz, 0.6 kW magnetron, modulated by a 50 Hz or 10 kHz power supply. The slot in the waveguide's upper wall enables a further view into it (in particular, for observing the fireball motion

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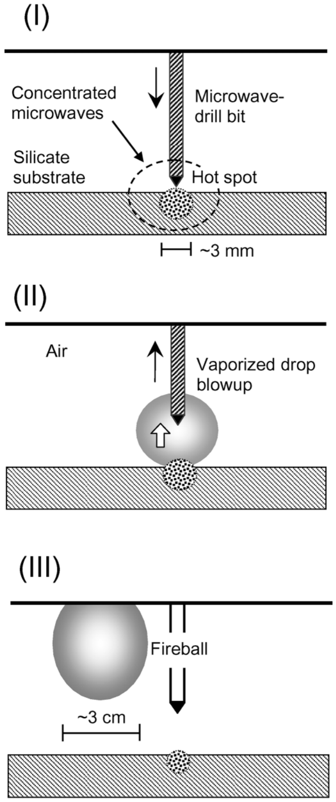

FIG. 1. An illustration of the fireball ejection from a molten hot spot in a silicate substrate: (I) a hot spot is induced in a thermal-runaway process by the microwave-drill technique on the substrate's surface. (II) The microwave drilling bit is pulled out slowly from the molten hot spot, dragging out a drop of the substrate material that blows up in the air. (III) The vaporized drop evolves to a stable fireball floating in the cavity's atmosphere.

along the waveguide). Fireballs were generated in this setup from substrate materials like silicon, glass, germanium, alumina, and basalt, in various shapes (e.g., plates, bulks, and powders).

A typical fireball initiation process is shown in Figs. 3(a)–3(c), as observed through the viewing vanes.

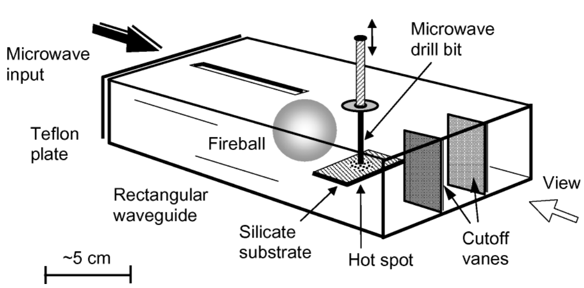

FIG. 2. The experimental setup consists of a waveguide fed by a 0.6 kW magnetron. The microwave energy is concentrated by the microwave-drill bit to form a molten hot spot in the substrate material from which the fireball evolves. A mirror made of vanes and the slot along the waveguide enable a direct view into the cavity.

First, the microwave-drill bit is brought into contact with the silicate substrate, hence concentrating the microwave power into the contact point within the substrate. A hot spot evolves then in a localized thermal-runaway process [20]. It reaches the melting-point temperature within a period of $\sim$1 second, and creates a molten hot spot [Fig. 3(a)]. The microwave-drill bit is then pulled out and detached from the molten hot spot while dragging a condensed, nearly vaporized drop out of the substrate. A stream of fire is ejected then from the molten hot spot forming a fire-column as shown in Fig. 3(b). Shortly after, this fire column rises, detaches from the hot spot, and forms a fireball in the air. The confined fireball flies up to the metallic ceiling, where it is slightly squeezed to a form of a Gaussian-like shape (upsidedown) as shown in Fig. 3(c). The floating fireball looks like a dense heavy vapor, almost liquid, glowing in yellow red, as shown in [21]. It becomes buoyant in the air and quivers elastically like a jellyfish. The floating fireball ($\sim$15 cm^3 in volume) may remain

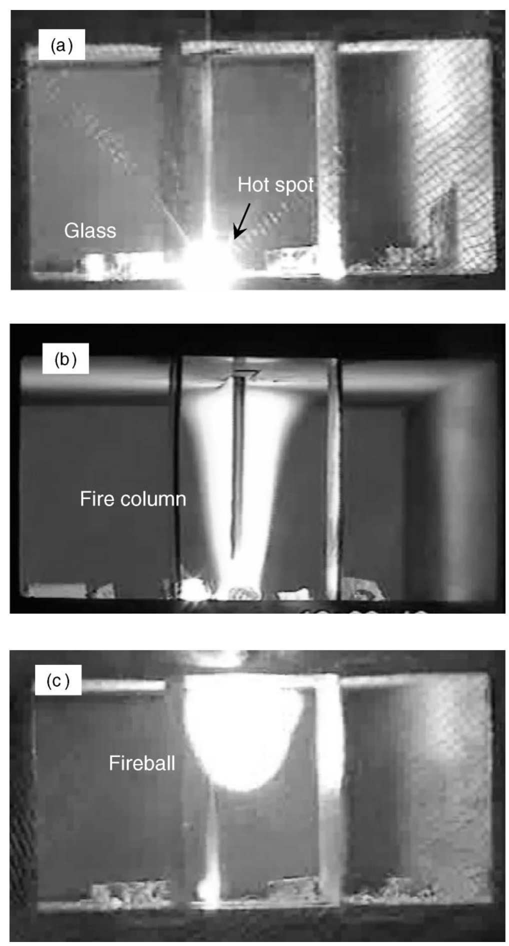

FIG. 3. The fireball initiation process in the microwave cavity, observed through the vanes shown in Fig. 2. (a) A molten hot spot is created by the microwave drill in the substrate material in a thermal-runaway process. (b) A fire column is ejected from the molten hot spot. (c) The fireball is detached from the hot spot and confined like a glowing elastic balloon buoyant in the air. The fireball is floating freely then near the cavity ceiling.

stable as long as the microwave power is on, and it continues to glow for another 30–40 ms after the microwave energy is turned off.

Other effects observed in this experimental setup include fireball bouncing and quivering, fire-column spinning like a tornado, and fireball traveling $\sim$0.5 m away along the waveguide toward the radiation source. Figure 4(a) shows a burned trace left by a traveling fireball that reached the Teflon plate situated 17 cm away at the microwave input port (shown in the left side of Fig. 2). Replacing the Teflon by a glass plate (2 mm thick) resulted in its slight melting, cracking, and finally breaking by the traveling fireball. The broken glass pattern was similar to the outer shape of the burned region in Fig. 4(a). The fire-column mode shown in Fig. 3(b) could be maintained for a longer time (before rising up and confining to a fireball form) provided that its feeding hot spot was kept active by the microwave-drill bit. Another effect observed occasionally was a secondary fireball excitation, as shown in Fig. 4(b). The new fireball moved away from the original fire column, and resided in the adjacent peak of the standing wave in the microwave cavity ($\sim$8 cm away). The originating fire column was then sustained together with its descendent secondary fireball, as shown in [21].

The ignition of the fireball is accompanied by a strong absorption of the microwave power. The reflections characterizing the empty cavity disappear when the fireball is excited, hence the microwave power is fully consumed by the fireball. It seems also that the fireball's impedance tends to match adaptively to the microwave source in a strongly coupled interaction. This finding could be related to the electrostatic-resonance hypothesis, referred also to fireballs in Ref. [12].

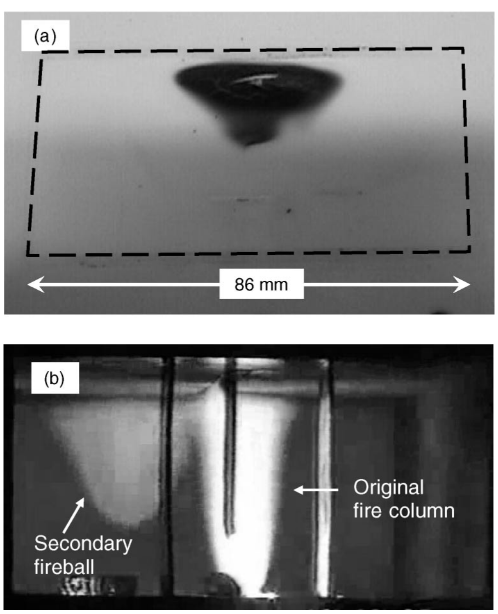

FIG. 4. Other effects observed in the fireball experimental setup: (a) a burned trace left by a traveling fireball on the Teflon plate shown in Fig. 2. The fireball flew along the cavity toward the microwave source ($\sim$17 cm). The burned trace shows the fireball's shape. (b) A secondary fireball excitation mode in which the original fire column remains. The secondary fireball moves to the adjacent peak of the standing wave in the cavity ($\sim$8 cm toward the magnetron) and resides there separately.

The microwave absorption effect in fireballs can be characterized by a simplified theoretical model, assuming a uniform plasma sphere in a rectangular waveguide. The complex relative dielectric permittivity $\varepsilon_s = \varepsilon' - j\varepsilon''$ is given for a plasma sphere by $\varepsilon' = 1 - \frac{\omega_p^2}{\omega^2+\gamma^2}$ and $\varepsilon'' = \frac{\omega_p^2\gamma}{\omega(\omega^2+\gamma^2)}$ [22,23], where ω, ω_p, and γ are the microwave, plasma, and collision frequencies, respectively. The plasma sphere suspended in the waveguide is modeled as a lumped load in parallel to a transmission line (the TE_{10}-mode waveguide) with a relative effective admittance [24]

$$\bar{Y}_L = \bar{G}_L + j\bar{B}_L \approx \frac{8\pi r^3}{ab}\frac{k^2}{\beta}\frac{3\varepsilon'' + j[(\varepsilon'')^2 - (1-\varepsilon')(2+\varepsilon')]}{(\varepsilon'+2)^2 + (\varepsilon'')^2}, \quad (1)$$

where $k = 2\pi/\lambda$ and $\beta = 2\pi/\lambda_g$ are the wave wavenumbers in free space and in the waveguide, respectively, a and b are the waveguide transverse dimensions, and r is the radius of the plasma sphere (assuming $r \leq \lambda/4$). The plasma sphere behaves as an ideally resistive load ($\bar{Y}_L = \bar{G}_L$) for $\gamma/\omega = \sqrt{(2+\varepsilon')/(1-\varepsilon')}$ and $\omega_p/\omega = \sqrt{3}$. The maximum power absorption in this resistive load in an infinitely long waveguide is attained for $\bar{G}_L = 2$, hence $\frac{\gamma}{\omega} = \frac{4\pi r^3}{ab}\frac{k^2}{\beta}$ [note that in free space, a small plasma sphere exhibits a strong absorption resonance at $\omega_p/\omega \approx \sqrt{3}$ and $\gamma/\omega = 0.67k^3r^3$ [23]].

The plasma ball initiation by microwaves resembles the plasmon resonance in noble metal nanoparticles in optical ranges [13–15]. In silver nanoparticles, the plasmon resonance is excited at a 355 nm wavelength ($r < 0.05\lambda$) [14], whereas $\varepsilon_s \sim -2.03 - j0.23$ [25] [note that $\varepsilon_s \sim -2$ is a singular point for the admittance in (1)]. The corresponding admittance (1) is $\bar{Y} \sim 0.8 + j0.2$, analogously to a $\sim$0.5 cm radius plasma ball at 2.45 GHz. The analysis shows that the latter may absorb $\sim$97% of the microwave power in our experimental setup. In steady state ($r \sim$ 1.5 cm), the dielectric and plasma parameters of the observed fireballs are estimated accordingly as $\varepsilon' \approx 0.2$, $\varepsilon'' \approx 1.3$, $\omega_p/\omega = \sqrt{3}$, and $\gamma/\omega \approx 1.2$ [note that $\omega_p/\omega \approx 1$ and $\omega_p/\omega \approx 2.7$ were estimated for larger fireballs, of $r \sim 0.8\lambda$ [11] and $r \sim 6.4\lambda$ [22], respectively]. Using Yasui's model of cooling by a blackbody radiation [26], the steady-state surface temperature is estimated to be 1300–2000 °K for a stable fireball of a $\sim$3 cm diameter as observed in our experiments (assuming an emissivity range of 0.2–1.0).

Fireballs produced in the method presented here from hot spots in solid substrate materials rather than by breakdowns in air [5–11] seem to contain components of the original substrate material, e.g., silica or alumina particles. Similarly to dusty and complex plasmas of macroparticles [27,28] these fireballs look as condensed, vaporized (partially liquefied) glowing bodies. In this aspect, the effect presented here, of fireball ejection from molten hot spot, resembles the soil lightning-strike mechanism proposed by Abrahamson and Dinniss for natural ball lightning [1,4]. Consequently, the microwave-drill effect illustrated in Fig. 1 simulates the atmospheric lightning that strikes the ground, melts it locally, and ejects the silicon-dioxide particles that form the natural fireball in the atmosphere.

The fireballs observed in our laboratory experiments differ, however, in several aspects from the ball lightning observed in nature [2]. The latter were described by eyewitnesses as possibly larger than our laboratory fireballs (up to $\sim$1 m versus $\sim$3 cm diameter, respectively), as persisting longer (for seconds versus our $\sim$0.04 s measurement), and as moving faster (0.1–10 m/s versus $\sim$0.3 m/s, respectively) at a roughly constant height. Natural ball lightnings were seen also as passing through glass windows, unlike our laboratory fireballs that slightly melt and break the glass, and then move forward. Several other features common to the natural ball lightning and to laboratory fireballs include the tendency to attach to metallic bodies (and moving or bouncing along them), the ability to be divided spontaneously [e.g., Fig. 4(b)], and their appearance in various shapes (e.g., ball and column shapes).

The laboratory demonstrations of fireball ejection from silicate substrates and the experimental method presented here may provide simple means for further studies of natural fireballs and related topics. Thus, it may contribute to the multidisciplinary effort to resolve the ball-lighting enigma. In practice, this controllable method of fireball generation from solid materials may introduce technological advantages for various applications of synthesized plasma balls in air atmosphere. These applications may include material processing, lightning, plasma confinement, and thin-film deposition [29].

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