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Spherical Plasmoids Formed upon the Combustion and Explosion of Nanostructured Hydrated Silicon

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The kinetics of the combustion and explosion of nanostructured hydrated porous silicon has been analyzed in a duration range from 100 μs to 1 s. It has been shown that the presence of hydrogen in silicon nanostructures increases the energy yield of oxidation processes leading to the formation of spherical plasmoids with a size of 0.1–0.8 m. Buoyancy in them can be compensated by the weight of the material particles formed inside and this compensation leads to a change in the velocity of plasmoids from 0.5 m/s to zero in the process of their cooling. It is hypothesized that a ball lightning appears due to the combustion and explosion of nanostructured hydrated silicon in spherical plasmoids.

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INTRODUCTION

In [1], researchers from New Zealand assumed that a ball lightning as a natural phenomenon is a result of the combustion or explosion of silicon clusters formed when a region of the ground is locally heated when normal linear lightning hits it. The authors of [1] even obtained a fragment of such silicon "fluff," but failed to achieve the combustion or explosion of this formation. After that, several works devoted to the combustion and explosion of porous silicon with the formation of plasmoids with a brightness temperature of above 2000°C were published [2–5].

The aim of this work is to analyze the explosion and combustion of nanostructured silicon in the presence and absence of hydrogen on its surface. Special attention is paid to the behavior of spherical plasma structures formed in these processes. Porous silicon layers formed as a result of the electrochemical anodizing of single-crystal silicon are used as a source of silicon nanoparticles.

EXPERIMENT

Porous silicon layers are formed by means of the electrochemical anodizing of *p*-type single-crystal silicon with a resistivity of 12 Ω cm in a 48% aqueous solution of hydrofluoric acid at a constant current density of 50 mA/cm^2. The anodizing duration is varied from 15 to 90 min in order to obtain porous layers with a thickness from 30 to 180 μm. Then, the experimental samples are placed in a 10% aqueous solution of KNO_3 and are dried at ~60°C.

The explosion and combustion of porous silicon are initiated thermally, mechanically, electrically, and optically. Thermal initiation is performed by means of contact heating to 900°C. Mechanical initiation is carried out by means of the scratching or pricking of the porous silicon surface using a metallic needle. Electric initiation is performed by passing an electric-current pulse through the structure under investigation. Optic initiation is carried out by laser radiation with a power of 40 MW/cm^2. Significant differences in explosive reactions in dependence on the method of their initiation are not revealed. Explosive reactions proceed at room temperature of the ambient air atmosphere with a controlled humidity of 50, 70, and 90%. The optical detection of an explosive reaction is performed by two video cameras with a speed of 60 fps, as well as by a silicon photodiode with further processing of its signal by a digital oscilloscope.

RESULTS AND DISCUSSION

The explosion and combustion of porous silicon are accompanied by the formation of a luminous ball with a diameter up to several tens of centimeters. Figure 1 shows the size of the flash appearing upon the combustion and explosion of porous silicon layers impregnated with KNO_3 as a function of the thickness of the layers under investigation and time of their storage after anodizing. It is worth noting that the size of the luminous flash is maximal for fresh samples, which is explained by a high content of hydrogen on the surface of silicon after anodizing. In the process of storage of fresh porous silicon layers, Si-H_x groups in them are replaced

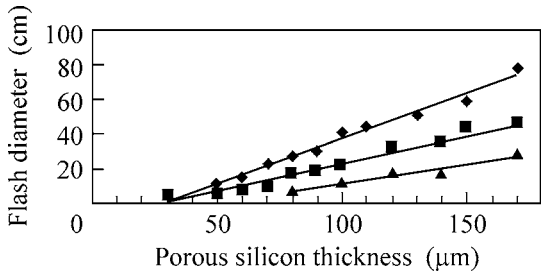

Fig. 1. Flash diameter upon the explosion of porous silicon impregnated with KNO_3 vs. the porous silicon layer thickness for samples with various storage times: (rhombs) fresh samples, (squares) samples after one-day storage, and (triangles) samples after two-day storage.

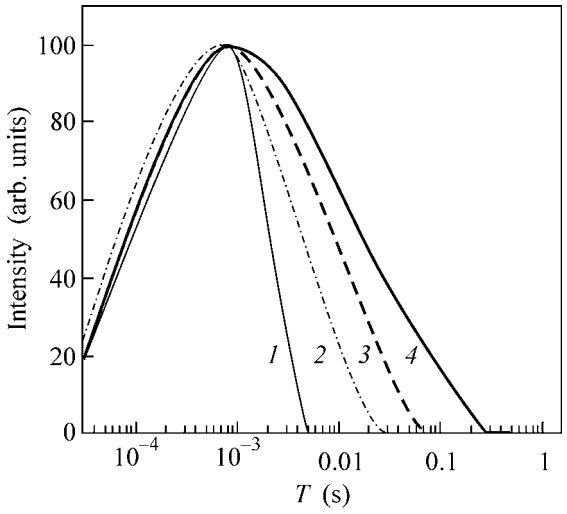

Fig. 2. Kinetics of change in the intensity of light from the explosion of porous silicon impregnated with KNO_3: (*1*) samples after one-day storage in air, (*2*) fresh samples after the explosion in an air atmosphere with a humidity of 50%, (*3*) fresh samples after the explosion in an air atmosphere with a humidity of 70%, and (*4*) fresh samples after the explosion in an air atmosphere with a humidity of 90%. The explosion is initiated by an electric pulse. The porous silicon layer thickness is equal to 100 μm.

by Si-O_x groups; i.e., the surface is dehydrated, which reduces the energy yield of the processes under investigation. Nevertheless, porous silicon retains the ability to burn and to explode after several days of storage. It is worth noting that the size of the luminous ball is determined by the amount of oxidized porous silicon.

Analysis of the kinetics of the increase and decrease in the light flash from the combustion of porous silicon shows a number of interesting features. The front of the increase in radiation intensity is almost unchanged under all conditions being studied, whereas the decrease in the radiation intensity is significantly determined by the regimes of the formation of porous silicon and humidity in the air atmosphere, where combustion occurs (Fig. 2). The duration of the explosion and combustion of fresh samples is equal to several tens of milliseconds and decreases to several milliseconds after one-day storage. Moreover, when these processes proceed in a humid environment, the radiation-intensity decrease time increases to fractions of a second. When explosion occurs in comparatively dry air, the flash is detected only on the surface of porous silicon. When fresh samples explode in a humid environment, the luminous sphere appears near the sample surface and is then separated from it and moves in air similar to a ball lightning as shown in Figs. 3a–3c. The division of the luminous ball into two or several luminous structures is sometimes observed (Fig. 3d).

We point to the kinetic and temperature parameters of the observed plasma structures. The luminous plasmoid moves upwards with a velocity up to 0.5 m/s, which is ensured by the local heating of a gaseous medium inside the ball. As the plasmoid is cooled, the velocity decreases. In certain cases, upward motion is first observed and then the plasmoid falls. In this case, after plasmoid attenuation, oxidation-reaction products [6], which are SiO_2 solid particles, burn out. Such a behavior can be explained by the fact that the weight of solid particles inside the plasmoid can compensate buoyancy, which leads to change in the direction of the plasmoid motion upon cooling.

The mechanism of forming a spherical plasmoid can be attributed to the formation of a vortex, where only solid products of the oxidation reaction can be confined. The vortex reduces the heat-conduction cooling of the plasmoid and particles inside it, which can significantly increase the lifetime of objects under investigation [7]. Moreover, the increase in the lifetime of plasmoids can be explained by the formation of a hydrated plasma [8]. The presence of water molecules in the atmosphere, which prevent the approach of plasma ions to each other and their recombination, can increase the lifetime of plasma structures by several orders of magnitude. As mentioned above, the surface of fresh porous silicon samples is strongly hydrated [9]. The explosion and combustion of such porous silicon are accompanied by the formation of water molecules ensuring the formation of hydrated plasma. This effect is strongly manifested when this explosive process proceeds in a humid atmosphere. When the explosion of fresh porous silicon occurs in an atmosphere with a humidity of close to 100%, the lifetime of individual plasmoids reaches about 1 s, which is comparable with the results obtained in [10, 11], where the lifetime of similar plasmoids exceeds 1 s.

The radiation spectra of formed plasmoids were analyzed in our previous work [12]. We only note that the brightness temperatures in most cases are in the range of 2000–3000°C, although flashes with higher temperatures are sometimes observed, which was also mentioned in [3]. It is known that silicon melts at

1415°C and boils at 3265°C. The respective parameters for silicon oxide are equal to 1713 and 2950°C [13]. For this reason, taking into account the brightness temperature range, one can assume that material particles inside spherical plasmoids at certain oxidation stages can be in solid, liquid, and gaseous states, which affects the velocity of spherical plasmoids.

The above explosive reactions in porous silicon are efficient in the presence of silicon structures with a size of 10 nm or smaller [14]. They are most intense in fresh porous layers, when the hydrogen content in them is maximal. According to our calculations, the energy yield from the oxidation of hydrated silicon is several times higher than the yield from usual pure silicon [15]. These are the most probable causes why the New Zealand researchers [1] could not initiate the combustion and explosion in nanosize silicon structures with particle sizes of 5–70 nm. Moreover, they studied unhydrated silicon.

It is known that the fundamental differences between combustion and explosion are the times of their development and the presence of a shock wave. Varying the thickness of porous layers and filling the porous surface with various oxidants, we reach the time of the processes under investigation from microseconds, corresponding to explosive processes, to several seconds, corresponding to slower combustion processes. In particular, porous silicon impregnated with KNO_3 undergoes combustion and explosion when its thickness is less and more than 60 μm, respectively [16]. It is worth noting that combustion and explosion do not exclude each other and can occur in the same experimental sample, for example, in porous silicon layers with variable porosity.

Figure 4 shows the most interesting photographs of luminous structures obtained upon the combustion and explosion of porous silicon samples. Figure 4a shows a corona accompanying the motion of the luminous ball. Such effect occurs due to afterburning of the scattering products of the oxidation reaction. Figures 4b–4d show the frames when the plasma structure, after separation from the initial sample, surrounds various objects without a destructive effect. In particular, neither the hand of a researcher initiating the explosion by means of mechanical contact nor an optical lens focusing the laser beam upon the optical initiation of the explosive process is subject to a noticeable action in contact with the formed plasma structures. Such behavior of spherical plasmoids indicates that their interaction with objects in contact is weak.

In view of the above properties, we propose a hypothesis of the appearance and development of a ball lightning. It supplements known representations [1, 10] and explains the diverse behavior of this mysterious natural phenomenon. The essence of the hypothesis is as follows. A linear lightning falling to the ground induces the formation of silicon particles, including those whose sizes are equal to several nanometers, as a

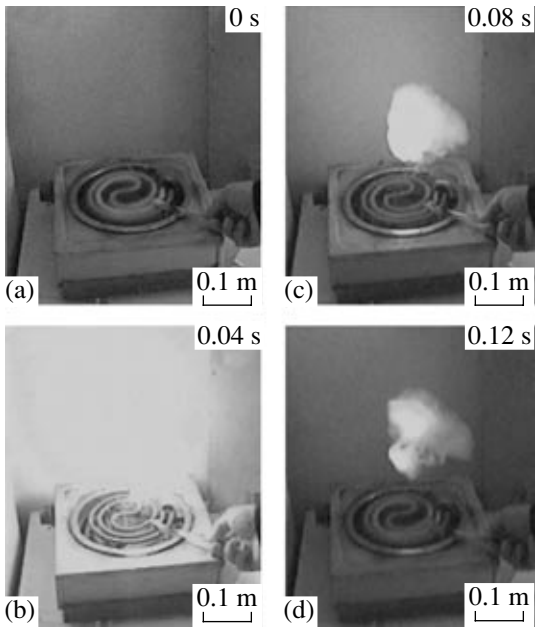

Fig. 3. Frames of the explosion of porous silicon impregnated with KNO_3 in an air atmosphere with a humidity of 90%: (a) the thermal initiation of the explosive process in the sample under investigation, (b) the separation of the spherical plasmoid from the sample under investigation, and (c, d) the motion of the luminous ball with the subsequent decay into two plasma structures.

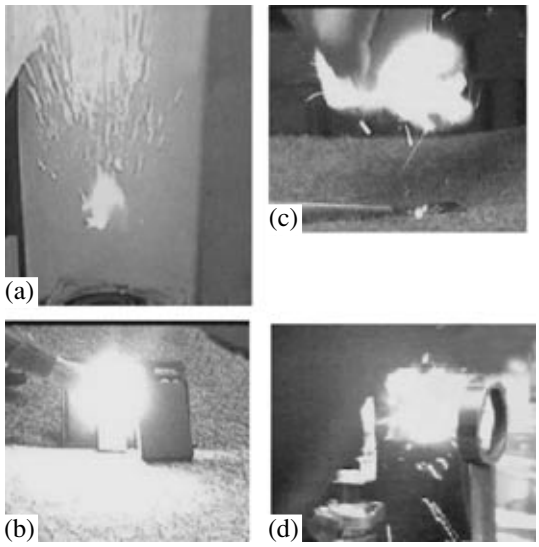

Fig. 4. Luminous structures obtained upon the combustion and explosion of nanostructured hydrated silicon: (a) corona accompanying the motion of the luminous ball (thermal initiation), (b, c) a sensible action of the formed plasma structure on a human being is absent (mechanical initiation), and (d) contact of the luminous ball with optical devices does not lead to destructive effects (optical initiation).

result of the local heating and evaporation of silicon from the ground and its further condensation in air. The surface of silicon nanostructures is covered with hydrogen atoms, because condensation occurs in a humid air atmosphere. Such nanoparticles are present in air in the form of a fractal cluster in the suspension state and are not manifested until the time, when their combustion or explosion is initiated by mechanical, thermal, or electric action. It is worth noting that silicon nanostructures with various sizes and configurations can burn and partially or completely explode, which corresponds to the diverse behavior of the ball lightning according to the description of spectators of this phenomenon. Moreover, it is important that the hydrated silicon surface and moisture of atmospheric air ensure the formation of the hydrated plasma in the process of combustion and explosion, which increases the lifetime of such a plasma to several seconds. Molecular oxygen, ozone in the atmosphere during and after a thunderstorm, and nitrogen compounds in a linear lightning channel can serve as oxidants [17]. As possible mechanisms of light emission in the processes under investigation, we point to thermal emission [1], the luminescence of the ionized particles of the hydrated plasma [10], the chemiluminescence of nanostructured silicon [18], and the photo- and electroluminescence of nanostructured silicon [19, 20]. To reveal the real contribution of each of the mentioned phenomena, additional experiments are necessary.

CONCLUSIONS

The combustion and explosion of nanostructured hydrated silicon in combination with the formation of the hydrated plasma surrounded by vortex fluxes can be manifested in the form of a 0.1–0.8 m luminous ball autonomously moving with a velocity up to 0.5 m/s. The plasmoid velocity decreases as it is cooled, because buoyancy ejecting hot plasmoids upwards is compensated by the weight of the products of the oxidation reaction. The lifetime of such plasmoids can reach 1 s.

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