Nanoscale Res Lett (2007) 2:319–330
DOI 10.1007/s11671-007-9068-2

NANO IDEAS

Ball Lightning–Aerosol Electrochemical Power Source or A Cloud of Batteries

Oleg Meshcheryakov

Received: 26 February 2007 / Accepted: 5 June 2007 /

Abstract Despite numerous attempts, an adequate theoretical and experimental simulation of ball lightning still remains incomplete. According to the model proposed here, the processes of electrochemical oxidation within separate aerosol particles are the basis for this phenomenon, and ball lightning is a cloud of composite nano or submicron particles, where each particle is a spontaneously formed nanobattery which is short-circuited by the surface discharge because it is of such a small size. As free discharge-shorted current loops, aerosol nanobatteries are exposed to a powerful mutual magnetic dipole–dipole attraction. The gaseous products and thermal energy produced by each nanobattery as a result of the intra-particle self-sustaining electrochemical reactions, cause a mutual repulsion of these particles over short distances and prevent their aggregation, while a collectivization of the current loops of separate particles, due to the electric arc overlapping between adjacent particles, weakens their mutual magnetic attraction over short distances. Discharge currents in the range of several amperes to several thousand amperes as well as the pre-explosive mega ampere currents, generated in the reduction–oxidation reactions and distributed between all the aerosol particles, explain both the magnetic attraction between the elements of the ball lightning substance and the impressive electromagnetic effects of ball lightning.

Keywords Ball lightning · Aerosol nanoparticles · Self-assembled clouds · Electrochemical oxidation and combustion · Low-temperature plasma

O. Meshcheryakov (✉)
Wing Ltd Company, 33 French Boulevard,
Odessa 65000, Ukraine
e-mail: wing@te.net.ua

Introduction

The nature of ball lightning still remains mysterious.

Let us remind ourselves of the unique range of properties this phenomenon possesses [1, 2]:

1. The pattern of ball lightning movement proves that it is a self-contained object with a density approximate to the density of the air (about 1.5–4.0 g/l);
2. An ability to restore a ball shape after a smoke-like penetration through narrow openings and an ability to retain its shape under conditions of strong atmospheric turbulence are evidence of the existence of a substantial surface tension (a mutual attraction between elements of the ball lightning substance);
3. The luminescence of ball lightning is mostly red-orange-yellow (about 60%), and is white in about 25% of observations;
4. Both low-temperature (not burning) and high-temperature ball lightning has been described by eyewitnesses who have had direct physical contact with ball lightning;
5. Ball lightning with diameters in the range of 10–30 cm has been observed most frequently, but objects of a much larger size have been described as well;
6. Its lifetime varies from seconds to several minutes;
7. Ball lightning either fades suddenly or disappears with an explosion;
8. A globe-shaped non-luminous cloudlet is observed sometimes within several seconds at the site of the ball lightning's disappearance;
9. The energy content of ball lightning with a diameter of about 20 cm has been estimated in the range of several tens to 200 kJ;

10. Ball lightning is sometimes able to emit infrared radiation (the sensation of thermal radiation), as well as emit strong radio noise, which has frequently been registered by radio receivers nearby;
11. Powerful electromagnetic impulses can be generated when ball lightning explodes (strong induced overvoltage and currents are demonstrated by both the breakdown of remote electrical equipment, and people far from the ball lightning explosion receiving electric shocks).

An adequate model of ball lightning should guarantee an explanation all of the aforesaid characteristics. Such a model should also explain the great variety and external dissimilarities of the conditions described by direct eyewitnesses of the process of ball lightning formation.

In particular, the process of ball lightning formation has been repeatedly and directly observable [2]:

(a) when lightning strikes trees or
(b) when lightning strikes lattice steel pylons or
(c) when lightning strikes open copper wires or
(d) when lightning strikes brick flues or
(e) in short circuits in electrical equipment or
(f) in powerful corona discharges of both natural and technological origin.

Models of ball lightning as a filamentary network of chain aggregates of nanoparticles slowly oxidizing in the air [3–6] allow us to explain the high energy content of this enigmatic object, though these models do not actually explain its ability to retain and easily restore its ball shape. Unfortunately the mentioned models do not also give an explanation for the various electromagnetic effects of ball lightning.

Model and Discussion

Here we suggest an alternative aerosol, but not aerogel, model for ball lightning, which is able to explain all the aforementioned properties, as well as a diversity of observable conditions and processes of ball lightning formation.

To facilitate discussion, we should briefly remind ourselves of the simplest design of electrochemical power sources.

To make an electrochemical power source (battery, accumulator, fuel cell, etc…), it is necessary to use at least three components:

An electrode—reductant, an electrode—oxidizer, and electrolyte, separating these electrodes (a substance aiding the interelectrode transport of ions, but not electrons).

Any pair of substances, each having a different electron affinity and contacting through a suitable electrolyte, is inevitably involved in a reduction–oxidation reaction and forms a certain electrochemical cell. Such a cell is generally able to generate a voltage in the range of a few tenths of a volt to 5 volts.

If one tries to mentally reduce the size of a standard battery, generating a voltage of about 1.5 volts, to the size of 100 nanometers or less (the characteristic size of a smoke particle), it can be seen that the electrostatic intensity inside such a nanobattery, between the spatially divided components of the reductant and the oxidizer, will considerably exceed the sparkover electrostatic intensity (at normal air temperature and pressure—about 30,000 volts/cm).

Thus, a galvanic cell made in the form of a composite submicron or nanoparticle suspended in the air, will be spontaneously shorted by an electric discharge, arising initially on the particle surface (then also in the adjacent air, in the immediate proximity to this surface) because the electrostatic intensity is too high.

We suggest a model where ball lightning is a cloud of composite particles, with sizes ranging from 5 to 1,000 nanometers, with each particle being a spontaneously formed nanobattery, short-circuited by a surface discharge.

Aerosol nanobatteries containing at least two key components of any galvanic cell—reductant and electrolyte—can be formed as a result of very different processes, including for example:

(1) the volume co-condensation of the mixed evaporated products of a spark-arc erosion of composite condensed substances, or
(2) an electrolysis of salt solutions (or salt melts) with following high-voltage electrospraying electrolysis-generated composite nanoparticles, or
(3) a high-voltage or plasma electrospraying composition of molten metals, their mixed oxides, and electrolytes.

As a result of these or similar processes, aerosol nanobatteries can apparently be spontaneously formed in at least two of their principal types—either in the form of composite nanoaggregates (Fig. 1) or in the form of nanocapsules (Fig. 2).

Although such separate particles-nanobatteries are capable of generating only a standard voltage of tenths of a volt to a few volts, the super-sparkover electrostatic intensity inevitably arises on their surface.

This leads to the development of an initial surface breakdown and to the excitation of microscopic contracted arc or arc-like discharges, running on the surface as well as in immediate proximity to the surface of each particle

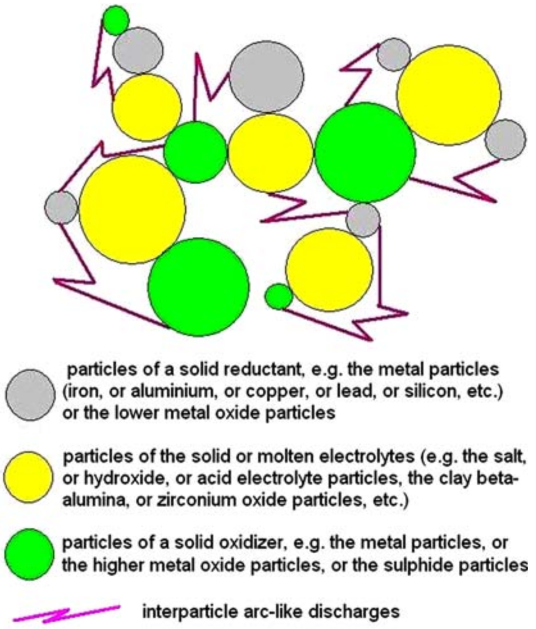

Fig. 1 Mixed sintered nanoaggregates of condensed smoke particles, containing solid reductant, electrolyte and oxidizer, inevitably form short-circuited aerosol nanobatteries

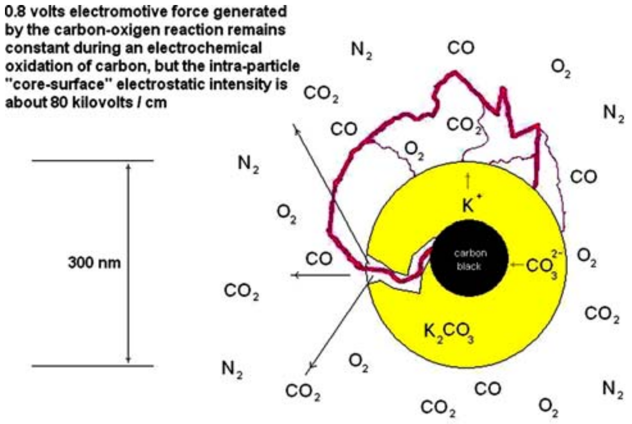

Fig. 2 Nanocapsules, containing a core reducing agent and surface electrolyte layer, form short-circuited aerosol nanobatteries

between the spatially divided areas, containing a reductant—fuel and oxidizer.

Apparently, it is important to note that the certain additional conditions are necessary to facilitate the initial development of the breakdown on the surface of the nanobatteries. One of these conditions can be the increased initial surface electroconductivity of nanoparticles, for example due to an initial surface hydration or surface carbonization of nanoparticles.

An alternative additional condition to facilitate the initiation of the breakdown on the surface of the nanobatteries can be their high temperature. In this case, the thermoionic and field emission can be major pre-ionization processes generating free seed electrons and initiating the surface breakdown in such white-hot nanobatteries immediately after their spontaneous air synthesis.

At the same time, the strong photoionization and/or local production of the seed gaseous ions from a preceding corona, preceding normal lightning, or from a preceding electric arc appear also to be high-performance potential pre-ionization processes facilitating the initiation of microscopic arc discharges on the surface of both high-temperature and relatively cold nanobatteries.

Thus, apparently, there are two major functions of the electric discharge prior to the formation of ball lightning:

(a) The synthesis of aerosol nanobatteries;
(b) The pre-ionization and ignition of the initial breakdown on the surface of the nanobatteries.

Generally speaking, aerosol nanobatteries can use both a condensed oxidizer (a third possible component contained in the nanoparticle) and external atmospheric oxidizers: first of all, atmospheric oxygen or water vapour, contacting with a core reductant of nanoparticles through a layer of electrolyte.

As the electrostatic intensity, generated in the nanobattery, and the surface-to-volume ratio are very high, a high electroconductivity of the intraparticle reductants and oxidizers is not necessary.

The arc or arc-like discharges, irregularly migrating on a surface of each particle, provide an uninterrupted neutralization of the generated electrochemically charge disbalancement between the heterogeneous areas of the particle, including the areas with a low conductivity.

Apparently, these arc or arc-like discharges are the main reason for luminescence of low-temperature ball lightning.

Discharge-shorted aerosol nanobatteries are exposed to powerful mutual attraction. This attraction is caused by magnetic fields, which are generated around of each particle by closed loops of the galvanic and discharge currents.

Separate, at first distant from each other, sparkling aerosol particles-nanobatteries approach together and form a luminous ball cloud under the influence of mutual magnetic attraction.

At the same time, since the galvanic currents flowing inside the aerosol particles and the surface discharge currents flowing mainly outside the particles form closed current loops, the galvanic and discharge currents inside such current loops are exposed to a mutual repulsion which in turn can result in the displacement of the initial surface discharges into the air space in proximity to the surface of the aerosol particles.

Gaseous products, for example, hydrogen, carbon monoxide, carbon dioxide, and the like, as well as the thermal energy, produced by each nanobattery as a result of intra-particle self-sustaining electrochemical reactions, excite a mutual repulsion of nanoparticles over short distances due to strong thermo- and diffusiophoresis.

Because of the powerful local generation of thermal energy and owing to surface discharges, the ionized gas layers develop around each aerosol particle. Over short distances, these plasma layers are able to overlap each other, forming branched interparticle series-parallel circuits and connecting separate aerosol nanobatteries in a united aerosol electrochemical generator. Accordingly, in these circumstances the substance of ball lightning is conducting and current-carrying low-temperature plasma with a condensed disperse phase—aerosol nanobatteries—continuously supporting a high ionization of the air disperse medium due to the surface and interparticle discharges.

It is important that a collectivization of the current loops of separate aerosol particles, due to the electric arc overlapping between adjacent particles, substantially weakens their mutual magnetic attraction over short distances.

It prevents an aggregation of particle-nanobatteries, and so they form a stable ball-shaped cloud with a density, slightly exceeding the air density (Fig. 3).

Various combinations of different reductants, electrolytes and oxidizers are able to form a great number of galvanic cells, including aerosol nanobatteries and clouds of them.

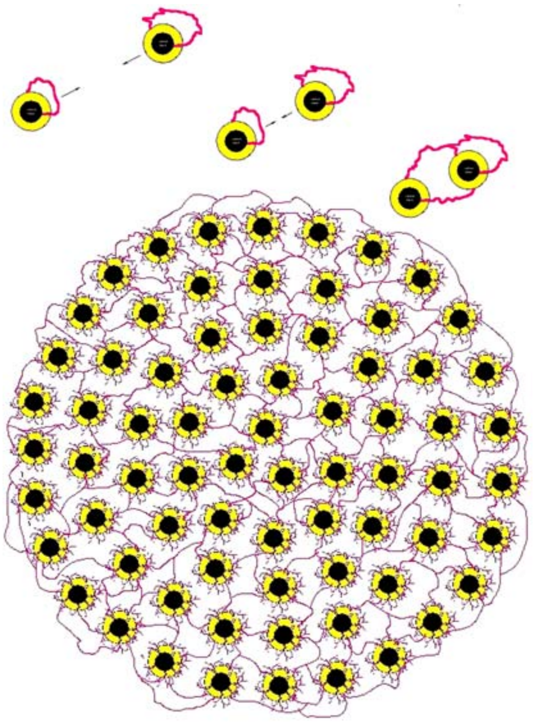

Fig. 3 Powerful interparticle magnetic attraction forms a stable cloud ball of short-circuited aerosol nanobatteries with total electric overlapping the surface discharges of separate particles

Apparently, one of the most widespread atmospheric reductants, which are frequently included in composition of the natural aerosol electrochemical power sources, is a soot carbon.

In such cases, created for example after lightning strikes a tree, a thin layer of potassium carbonate (an essential component of wood ash), co-condensed on the surface of black carbon nanoparticles, can play the role of a high-performance molten electrolyte in the spontaneous formation of high-temperature molten-carbonate aerosol fuel cells.

A volume condensation of evaporated carbon with the production of black carbon nanoparticles is immediately followed by the condensation of molten carbonate layers on the surface of the hot carbon particles (in these circumstances, the charged black carbon particles are condensation nuclei for evaporated carbonates). Such a process of high-temperature co-condensation of the carbon fuel and carbonate electrolyte can result in the spontaneous creation of aerosol electrochemical generators with separate core-shell nanobatteries (nanocapsules), suspended in an atmosphere containing oxidizer.

The internal allocation of fuel (the core carbon), and the surface position of molten carbonate electrolyte on the carbon particles, enables it to practically completely protect the carbon from normal high-temperature oxidation, and simultaneously allow its efficacious electrochemical oxidation by the atmospheric oxygen (Fig. 2).

In black carbon nanoparticles encapsulated in the molten carbonate electrolyte, at a temperature of nearly 900 °C, electrochemical (CO_3^{2-} ion-mediated) oxidation of the carbon should arise spontaneously and then be thermally self-sustained.

The gaseous products of electrochemical oxidation of the core carbon, i.e., CO_2 and CO, perforate the surface molten carbonate layers continuously, forming dynamic self-healed pores in these layers. As a result of the reaction carbon with carbonate CO_3^{2-} ions, the carbon core acquires negative charge, while external surface of molten potassium carbonate shell acquires positive charge due to residual uncompensated (surplus) potassium K^+ ions. Thus, electrochemical potential difference arises, and the CO- and CO_2- generated dynamic pores in molten carbonate shell are initial channels for the arc discharges starting from carbon core of the nanobatteries to their external surface.

Thus, each separate battery-nanocapsule of this aerosol electrochemical generator contains the black carbon nanoparticle as the core carbon anode, while external surfaces of molten potassium carbonate shells of the batteries-nanocapsules are oxygen-depolarized cathodes of such aerosol nanobatteries supplied with air and CO_2.

It is worth mentioning that the core carbon electrode in these nanobatteries is an anode only within the framework of electrochemical interpretation. This carbon electrode is charged negatively, and in this case the carbon electrode simultaneously can be named as an electron-emitting cathode (within the framework of electrophysical or electronic interpretation).

Apparently, high-temperature cathode spots can arise on the surface of the white-hot core carbon nanoparticle. These cathode spots emit the seed electrons for arc discharges due to powerful local thermoionic and field emission. The current density within such arc cathode spots can be extremely high, and high-power electron avalanche breakdown develops from cathode spots inside the CO- and CO_2- generated dynamic pores. As soon as the electron avalanches reach an external surface of the core-shell nanobattery, the gas phase electrons are captured by the surface excess potassium K^+ ions and electronegative gas molecules. On the external surface of molten potassium carbonate shell, the cathode reaction, involving electrons, O_2, CO_2, O_2^- and metallic potassium (the primary product of the K^+/electron recombination), regenerates new potassium K^+ and carbonate CO_3^{2-} ions. Further the carbonate ions again repeat process of the oxygen transport through molten potassium carbonate shells to the core carbon anode…

Probably, enormous reaction surface inherent in the nanobatteries and aerosol electrochemical generators, high-energy plasma chemical reagents (similar to gas phase electrons and ions) involved in electrode reactions, as well as high work temperature specifically inherent in carbon/air aerosol electrochemical generators cause very high effective power of electrochemical processes even without involving any additional cathode catalysts.

Interestingly, non-aerosol pilot plants of high temperature, molten electrolyte electrochemical cell devices, able to direct converting carbon black fuel to electrical energy with a voltage of 0.8 V and efficiency 80%, were recently developed and investigated [7].

Such carbon fuel cells, chemically similar to described here hypothetic aerosol carbon/air electrochemical power sources, generate electric power from an electrochemical reaction similar to the combustion reaction of carbon:

$$C + O_2 = CO_2 \quad \Delta H^{\circ}_{298k} = -94.05\,\text{kcal/mol}, \tag{1}$$

The net reaction (1) can be written as the sum of two half-cell reactions, involving the carbonate ions

$$O_2 + 2CO_2 + 4e^- = 2CO_3^{2-} \qquad \text{(cathode reaction)} \tag{2}$$

$$C + 2CO_3^{2-} = 3CO_2 + 4e^- \qquad \text{(anode reaction)} \tag{3}$$

the carbon anode may also partially oxidize to CO in a competitive reaction:

$$C + CO_3^{2-} = CO + CO_2 + 2e^- \qquad \text{(anode reaction)} \tag{4}$$

Taking into account the experimentally obtained parameters of the voltage and the efficiency of high temperature carbon/air fuel cells with molten-carbonate electrolytes [7], let us try to estimate the potential characteristics of analogous aerosol electrochemical power source, i.e., the potential characteristics of the carbon/air ball lightning.

Let a 20 cm diameter ball lightning be formed after lightning strikes a tree.

Let the density of this ball lightning be about 2–4 g/l. Let the fuel of this ball lightning aerosol electrochemical generator be black carbon, with the electrolyte being a dynamically porous layer of molten potassium carbonate, condensed on the surface of black carbon aerosol nanoparticles.

The volume of such a ball lightning is about 4 l, and the mass of the carbon fuel is 4 g at least.

As the heat of the carbon combustion is about 33 kJ per gramme, the energy content of this ball lightning can be about 130 kJ.

At the direct electrochemical conversion of this energy, the total electromagnetic energy of internal discharge currents of this ball lightning will reach about 100 kilojoules if the efficiency of electrochemical conversion is 80%.

Accordingly, a density of magnetic energy

$$\omega = B^2 / 2\mu_0\mu \tag{5}$$

where B is magnetic flux density (tesla), $\mu_0 = 4\pi \times 10^{-7}$ is permeability constant (H/m), and $\mu \approx 1$ is the black carbon aerosol's magnetic permeability, will reach about 20 kJ/l, while the magnetic pressure P, maintaining the ball lightning sphericity and being equivalent to ω, will reach approximately 200 atmospheres. Accordingly, in this particular case, the value of the interparticle local magnetic fields B will reach about 7 tesla.

It explains, for example, why a powerful air drag is not able to tear the ball lightning substance apart, when the ball lightning escorts aircraft.

So, let the lifetime of such a high-temperature aerosol electrochemical power source be about 50 s, during which it gradually spends its energy and then quietly fades.

Consequently, the average electromagnetic power of this aerosol power source should be about 2 kW (i.e., 100 kJ/50 s).

The visible luminescence of this ball lightning is caused by the plasma radiation of the surface particle and interparticle arc-like discharges, a high-temperature luminescence of the hot particles, as well as additional luminescence from the direct oxidation of carbon and carbon monoxide (a competitive process, proceeding simultaneously with electrochemical oxidation and connected with the partial intracarbonate diffusion of molecular oxygen).

According to the calculated value of average electromagnetic power above, and according to the above-mentioned value of the voltage of the non-aerosol prototype of the carbon black electrochemical power source, the average total value of internal discharge currents of this ball lightning should be about 2,500 amp (i.e., 2 kW/0.8 V).

The value of these currents, distributed between all the nanoparticles, explain the existence of a powerful mutual magnetic attraction between the particles, a high surface tension value of the ball lightning substance, as well as the strong radio-interferences effects of ball lightning.

Let the ball lightning exist quietly for only 10 s, and then it explodes as a result of the self-propagation of local thermal fluctuations.

At the moment of explosion, the temperature, ion conductivity of the electrolyte, rate of electrochemical reactions, discharge currents, and energy-release strongly increase.

Assuming that the explosion time is about 0.1 seconds and that the main part of the residual chemical energy of this ball lightning is converted into electromagnetic energy during this time, then obviously the total strength of the pre-explosive discharge currents can reach about 1,000,000 amp.

Assuming that the ball lightning explosion time is shorter, the total strength of the pre-explosive discharge currents can reach even greater values.

A fast increase of discharge currents to such high values during the explosion and following fast droop of current to zero can explain the origin of powerful electromagnetic pulses and various strong distant induction effects, observed by eyewitnesses of ball lightning explosions.

The principle of potential energy minimization allows us to expect magnetic ordering effects and the internal dynamic self-compensation of powerful local magnetic fields inside this system of dipole–dipole magnetically interacting free aerosol current loops. Therefore under conditions of weak external magnetic fields and at sufficient distances from the ferromagnetics, ball lightning as a whole can have only a minimal uncompensated magnetic moment.

Otherwise, and also, apparently, at the moment of the explosion, the uncompensated magnetic moment of the ball lightning can be substantial. It can lead to effects of attraction of ball lightning towards ferromagnetics, permanent magnets or current sources of external magnetic fields.

The magnetic fields, measured inside the clouds of nanobatteries, should, apparently, strongly fluctuate. The large clouds or very large clouds (e.g., fog) of nanobatteries are, probably, also able to interfere with radio communication owing to both the shielding and the radio noise generation.

Other Possible Components of Nanobatteries

The widespread atmospheric aerosol fuel—black carbon nanoparticles—nevertheless is only one of numerous potential contenders to work as a reductant in the aerosol electrochemical power sources.

In addition to the black carbon, many unoxidized substances (e.g., similar to Si, Zr, Fe, Cu, Al, Sn, Pb, B, Ca, W, S etc.) or suboxidized substances (e.g., similar to FeO, Cu_2O, SiO etc.), hydrides, carbides, sulphides, silicides as well as fuel gases absorbed by nanoparticles, could apparently work as other probable reductants in the natural aerosol nanobatteries.

Probably, even some salts with a deficiency of oxygen, e.g., similar to nitrites (or sulphites) being electrosprayed or condensed from vapour in the local atmosphere of the nitric oxide and nitrogen dioxide (or correspondingly in the sulphur dioxide atmosphere) in the form of submicron or nanoparticles could also work in the natural aerosol low-power nanobatteries-capsules as high-performance salt reductants. The subsequent air oxidation of these aerosol salt particles could cause the growth of nitrate or sulphate electrolyte layers on their surface. In these circumstances, the external oxidizer—oxygen—can react with the reductant only through the growing shell of a hydrated or molten electrolyte, in particular, a nitrate or sulphate electrolyte. Such a concentric relative position of a reductant, electrolyte and oxidizer is one of the important conditions for the promotion of the preferred electrochemical, ion-mediated oxidation of the core salt reductant instead of its molecular oxidation.

The potential natural sources of the electrolyte nanocomponents for low-temperature ball lightning could be, probably, atmospheric hygroscopic substances, in particular, salt (first of all, chloride or sulfate) cloud condensation nuclei, or the aerosol products of the erosion of nitrate, carbonate or phosphate minerals as well as atmospheric aerosol products of the volcanic origin (Fig. 4).

At the same time, potential electrolytes for ‘‘high-temperature’’ ball lightning, i.e., for ball lightning with temperatures of aerosol nanobatteries in an interval of 100–2,000 °C, could be substances similar to phosphoric acid, sulphuric acid, molten salts, molten or softened natural silicates, oxide and oxynitride glasses, solid metal-oxide electrolytes similar to clay beta-alumina with a wide range

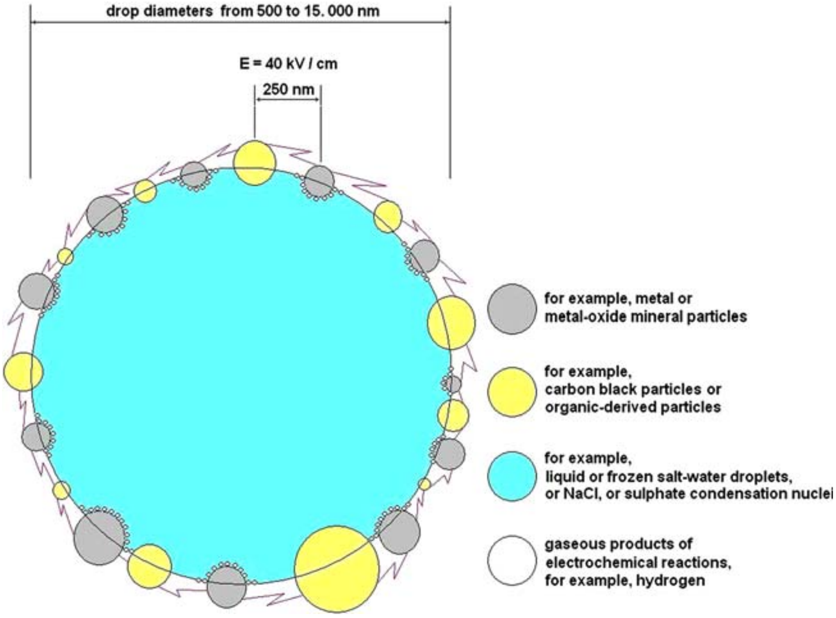

Fig. 4 Low-temperature clouds of nanobatteries can also be spontaneously created on the basis of composite atmospheric particles, containing for example a mixture of hygroscopic condensation nuclei, metal or metal-oxide mineral particles, and organic nanoparticles

of the potential high-mobile ions—at 250–300 °C—which may be e.g., Na^+, K^+, Li^+, Ag^+, H^+, Pb^{2+}, Sr^{2+} or Ba^{2+}.

In addition, possible electrolytes for natural or artificial ''high-temperature'' batteries-nanocapsules apparently could also be the solid electrolytes on the basis of the zirconium oxide solid solutions, such as yttria-stabilized zirconias, calcia-stabilized zirconias, magnesia-stabilized zirconias etc., or some nitride solid electrolytes, e.g., similar to Li_3N, or the solid electrolytes on the basis of some composite oxides, e.g., similar to $Li_{2+x}C_{1-x}B_xO_3$, $Li_{4+x}Si_{1-x}P_xO_4$ and $Li_{5+x}Ag_{1-x}Si_xO_4$ as well as the solid electrolytes on the basis of oxynitrides, e.g., similar to lithium phosphorous oxynitride electrolytes.

Generally speaking, it is necessary to note that the processes of oxidation of aerosol reductant particles can often result in the formation of electrolyte layers on the surface of these particles in the form of electrolyte hydrates, electrolyte melts, or solid electrolyte layers instead of the ordinary dielectric oxide layers. Such surface electrolyte layers can significantly reduce the standard rates of oxidation of these aerosol particles by molecular oxygen. At the same time, such electrolyte layers can naturally incite the subsequent competitive process of electrochemical oxidation of the core reductant of these particles. The capsules-nanobatteries with such surface electrolyte layers can be spontaneously formed for example, during the oxidation of primary aerosol particles in a damp atmosphere, in an atmosphere containing carbon dioxide, as well as in an atmosphere containing an acid or a free halogen. In similar circumstances, e.g., the alkali or alkali-earth metal aerosol particles will be covered with growing hydroxide, carbonate, or with halogenide electrolyte shells instead of growing oxide layers.

It is worth mentioning here that the growth of the surface hydrated layers of hydroxides or hydroxocarbonates, instead of the expected oxide layers, are a common outcome of open-air oxidation for many metals (in particular: iron, copper, aluminium, brass, bronze, tungsten etc.).

Such ordinary surface layers, for example the patinas layers in the form of hydrated $Cu(OH)_2CuCO_3$ and $Cu(OH)_2CO_3$, or layers of hydrated aluminium oxide hydroxide, AlO(OH), or layers of hydrated aluminium hydroxide, $Al(OH)_3$, or layers of rust in the form of hydrated FeO(OH) and $Fe(OH)_3$, are electrolyte substances which are thermostable enough to form both low-temperature and intermediate-temperature aerosol nanobatteries.

For example, the decomposition point of $Cu(OH)_2CO_3$ exceeds 200 °C. AlO(OH) is converted into Al_2O_3 at a temperature of ~420 °C, the melting point of $Al(OH)_3$ is ~300 °C, $Fe(OH)_3$ is converted into Fe_2O_3 at a temperature of ~500 °C.

At the same time, the capsules-nanobatteries with gradually developing surface layers of the oxide, nitride and oxynitride solid electrolytes can also be spontaneously formed at the high-temperature oxidation of many aerosol metal particles (e.g., zirconium-calcium, zirconium-yttrium alloys, lithium or lithium alloys, aluminium alloys etc.) in a dry air or a pure nitrogen atmosphere.

One can see that a lot of the oxidation processes in the various local atmospheres, also including the ordinary processes of open-air oxidation, can cause the growth of hydrated, molten, or solid electrolyte layers on the surface of the aerosol particles-reductants instead of the dielectric oxide layers.

The formation of the similar electrolyte shells on the surface of aerosol particles, due either to their atmospheric oxidation or to the other above-mentioned processes, e.g., similar to the volume co-condensation of the mixed vapour of reductants and electrolytes, can initiate an alternative electrochemical ion-mediated oxidation of the core particles reductants and, under pre-ionization conditions, convert such particles into aerosol discharge-shorted batteries-nanocapsules.

It is possible that in addition to external gaseous oxidizers, some metals, their higher oxides, superoxides, ozonides, sulphides, chlorates as well as sulfur could, apparently, act as condensed oxidizing components, included in the composition of aerosol nanobatteries during their spontaneous air synthesis.

Competition Between the Processes of Normal and Electrochemical Oxidation Inside Nanobatteries

Certainly, it is clear that the fuel for ball lightning—in the form of aerosol submicron and nanoparticles—can only be made inside the local air volume with an initial deficiency of oxidizers. As is well known, such a local temporary deficiency of oxidizers can be spontaneously achieved by various means. For example, it can be achieved with the help of local ‘‘burning’’ oxidizers inside a confined space due to the substantial excess vapour of the future nanoparticle ball lightning fuel. Another probable means for the local temporary neutralization of the influence of atmospheric oxidizers during ball lightning formation is the accidental simultaneous process of the generation of a reducing atmosphere of additional gas reductants—hydrogen, carbon monoxide, hydrogen sulphide etc. This essential requirement of nanotechnology of metals—the presence of an inert or reducing atmosphere at the manufacture of oxidable nanoparticles—is completely applicable to the technology of nanoparticle ball lightning [5].

Therefore, the initial stage of the formation of ball lightning—the process with a local deficiency of oxidizers—enables the spontaneous self-assembly of the aerosol nanobatteries without a premature oxidative inactivation of the reductant components.

However, normal atmospheric oxidation can also compete with the process of electrochemical oxidation after an initial formation of the batteries-nanocapsules is completed, and ball lightning is now in the oxidizer-enriched air.

In this case, layers of dielectric oxides can theoretically appear on the surface of the core reductant, e.g., due to the partial diffusion of molecular oxygen through the protective shell of an electrolyte, and complicate further charge transfer and the normal work of nanobatteries.

But such an evolution of the nanobatteries work process requires the following:

(1) the oxides, growing inside the nanobattery, should be condensed substances, but not gases, e.g., similar to CO_2 or SO_2;
(2) these oxides should form very dense, compact, non-nanoporous dielectric layers directly contacting with the hydrated or molten electrolyte;
(3) at that, such oxide layers should be electrolyte-insoluble;
(4) besides this, these layers should not react with the electrolyte, water vapour, or oxides of nitrogen, as the similar chemical reactions will convert the dielectric oxides to electrolyte-salts, e.g., silicates, hydroxides, nitrites, nitrates etc.;
(5) the oxide, nitride, or oxinitride layers generated should not be the solid electrolytes in themselves;
(6) the oxide, nitride, or oxinitride layers generated should not be the electronic semiconductor or the electronic conductor, including at the high temperatures, e.g., similar to SnO_2, In_2O_3, Al-doped ZnO, Y–Ba–Cu–O, Pb–Bi–Sr–Ca–Cu–O, PbO_2 etc.;
(7) such oxide dielectric layers should also be proof against an influence of reductants similar to carbon, carbon monoxide, or hydrogen, i.e., to an influence of the reducing substances which are either included into the nanobattery composition during the spontaneous synthesis of nanobatteries, or these reducing substances are synthesized during the work of the nanobatteries.

As is obvious, the list of necessary requirements for the properties of the substance of the dielectric oxide layers, which can potentially complicate the work of the nanobatteries while growing on the surface of the core reductants, strongly limits the possible choice of such a detrimental (for our model) substance.

Some Collective Effects Inside a Cloud of Nanobatteries

The collective effects obviously should be of great importance in the life of aerosol clouds of nanobatteries. Each nanobattery is indeed capable of generating a voltage only of about 1 V. But complexes—aggregates containing thousands and millions of separate galvanic nanocells can be formed due to accidental statistic processes of aggregation in a high-density hot aerosol during ball lightning formation. Repeated chaotic connections of a great number of nanobatteries in such dynamic complexes provide occurrence of plural series-parallel gas-discharge electric circuits inside the ball lightning. Statistic formation of such macro-aggregates of nanobatteries with accidental series connections between them can provide arising dynamic ‘‘voltaic piles’’ of nanobatteries with enormous resulting voltage. These spontaneous multiple high-voltage dynamic nanoparticle generators will promote further electric collectivization of the current loops of separate aerosol nanobatteries through interparticle high-voltage discharges. Apparently, not only local processes of the initial mechanical agglomeration of nanobatteries, but also the high initial electroconductivity of the seed low-temperature plasma of the preceding spark or corona discharge can contribute to the spontaneous electrical connection of separate nanobatteries into plasma-united series-parallel circuits.

Many billions of nanobatteries, electrically united by low-temperature plasma and electrically feeding this plasma, are contained inside a ball lightning cloud, which thus can be both a high-voltage and a high-current electrochemical aerosol generator.

Probably, the very long sparks from ball lightning to earthed objects, sometimes observable by eyewitnesses, even inside shielded rooms [2], can be a product of the super high voltage generated by the plural voltaic piles of nanobatteries, arising on the surface of ball lightning.

Apparently, a degree of electric collectivization of separate nanobatteries into plasma-united aerosol electrochemical generator can depend on a lot of linked conditions (e.g., on the temperature of nanobatteries, their form and concentration, a degree of the plasma ionization and a presence of ionized alkaline impurity, on magnetic permeability of nanobatteries, their gassing, on the currents of nanobatteries etc.). As the degree of electrical connection of the nanobatteries inside different aerosol electrochemical generators can be very various, electric power of such aerosol generators can also be alternatively redistributed either to maximal currents of separate nanobatteries, or to maximal voltage of dynamic voltaic piles of plasma-connected nanobatteries, or to intermediate values of currents and voltages adequate to complete electric power of the aerosol electrochemical generator.

Above, we have also mentioned the possibility of the generation of high and even extremely high currents inside the ball lightning electrochemical aerosol generators.

At first sight**,** this possibility seems to be highly exaggerated.

However let us consider it in detail a little further.

If either the ion conduction of a nanobattery electrolyte or the electron conduction of a nanobattery reductant is very low, the galvanic and discharge currents inside a cloud of such nanobatteries, as well as the luminosity of such a cloud can also be very low, so that such ball lightning is hardly visible in bright sunlight, while the lifetime of this low-power ball lightning can be, on the contrary, increased.

If the substance of the nanobattery reductant (e.g., similar to carbon, an extrinsic semiconductor, or metal) and the substance of the nanobattery electrolyte (e.g., similar to salt/acid/alkaline melts or salt/acid/alkaline hydrates) is moderately or highly conductive under the given conditions of temperature and air moisture, the discharge currents inside such a cloud of the aerosol nanobatteries can be moderate, high, or even extremely high.

Apparently, the currents in the range of several amperes to several thousand amperes distributed between all the aerosol particles of the cloud are the currents of a quiet state of ball lightning.

Discharge currents in the range of several thousand to several million amperes distributed between all the aerosol particles, are apparently pre-explosive and explosive currents of ball lightning.

At the same time, we believe that the generation of such extremely high discharge currents inside ball lightning is also absolutely realistic.

Let us prove it. Let black carbon, i.e., a substance with quite a low conductivity, be the core reductant of the nanobattery.

Let an average diameter of the carbon core reductant particle be about 100 nanometers (Fig. 2).

An average cross-section area of this carbon particle is $\sim 7.8 \cdot 10^{-11}$ cm^2.

An average volume of carbon particle is $\sim 5.2 \cdot 10^{-16}$ cm^3.

An average mass of carbon particle is $\sim 1.2 \cdot 10^{-15}$ g.

So, the average number of nanoparticles in a 20 cm diameter ball lightning is $\sim 3.3 \cdot 10^{15}$ nanoparticles. The average cross-section area of carbon nanoparticle is of the order of the area where the galvanic current flows through the nanoparticle, i.e., about $7.8 \cdot 10^{-11}$ cm^2.

The total area where the total current flows through all the aerosol nanoparticles will accordingly be about $2.6 \cdot 10^5$ cm^2. So, the total area is ~26 m^2.

A total electrical current of 10^6 amp (distributed between all the aerosol particles) through total area $2.6 \cdot 10^5$ cm^2 will result in a current density of about 3.8 amp/cm^2.

However, this is an absolutely acceptable current density for hot carbon. For example, the standard recommended current density through carbon electrodes in a continuous furnace process is ~27 amp/cm^2 [8].

Thus, an extremely large total area, where intraparticle galvanic currents flow simultaneously through all the aerosol submicron or nanoparticles, causes a low average current density, which is absolutely acceptable for the normal work of hot carbon and the overwhelming majority of hot extrinsic semiconductors and metals as possible reductants in the aerosol electrochemical generators.

As one can see, enormous reaction surfaces inherent in aerosol electrochemical generators readily enable to generate mega ampere currents and, consequently, mega watt electric power.

Therefore too high conductivity of the nanobatteries components (in particular, electronic conduction of reductants and ionic conduction of electrolytes) can considerably shorten a lifetime of ball lightning.

Ball-lightning-like Objects and Natural Thunderstorm Related Ball Lightning

As is well known [1, 2, 9–11] manmade ball-lightning-like objects can be generated with the aid of a great number of various methods. The superficial resemblance between the properties of these objects and the properties of the natural thunderstorm related ball lightning can be very significant. Sometimes, only small formal distinctions raise doubts about the identity of the manmade and natural objects, e.g., the lifetime distinctions, or the electromagnetic properties distinctions, or the density distinctions etc. Ball-lightning-like objects, generated by electrical arc discharges from *p*-type doped silicon wafers in recent experiments [9], are undoubtedly the most impressive experimental advances in ball lightning science. Really, mentioned luminous objects are very similar to natural ball lightning. However, the authors of these extremely interesting experiments correctly discuss two important limitations: ‘‘First, the production of the luminous balls is not under complete control. Second, free-floating balls were not observed.’’

Indeed, these limitations unfortunately leave a question open concerning the identity of the mentioned ball-lightning-like objects and natural thunderstorm related ball lightning.

Here, we would like to consider only two different models as possible interpretations of the experiments [9].

The first model assumes that the ball-lightning-like luminous balls described in [9] are clouds of nanobatteries. *P*-type doped silicon evaporated by arc discharge is condensed in the form of aerosol submicron or nanoparticles of amorphous silicon with boron trioxide microaddings. Thus, a condensation cloud of burning hot nanoparticles of amorphous silicon is a cloud of potential silicon core reductants for aerosol nanobatteries. At 29 °C room temperature and a relative humidity of 70% mentioned in [9], i.e., under conditions of very high absolute humidity of ambient air and consequently under conditions of extremely high vapour pressure of the water in immediate proximity to high-temperature ball-lightning-like objects, the oxidation of the aerosol nanoparticles of amorphous silicon will result in the formation of electrolyte layers of silicic acids (by reaction SiO_2 with water vapour) on their surface, instead of the expected SiO_2 dielectric surface layers. As is well known [12], at high temperatures silica scale layers are readily converted in the presence of water or water vapour to form silicic acids. Although these electrolyte silicon species are volatile at such temperatures, their ablation is compensated for by the persistent formation of new silicic acids layers on the surface of the silicon aerosol particles under conditions of high air moisture, i.e., in this case the processes of thermal ablation and water-mediated growth of such silicic acids layers are in dynamic equilibrium.

Thus, ball-lightning-like luminous clouds of discharge-shorted nanobatteries with silicon core reductants, dynamic electrolyte shells of hot silicic acids and external air oxidizers, can theoretically be created in experiments similar to [9] due to high air moisture.

The indirect verification of this model can easily be realized by a variation of the absolute humidity during experiments similar to [9].

If the model works, an increase of the absolute humidity will increase the reproducibility of experiments, while lowering the absolute air humidity will decrease the reproducibility of the experiments (i.e., the probability of generating ball-lightning-like luminous balls).

As the second model, it is possible to assume that ball-lightning-like objects generated in [9] are only small pieces of semiliquid ‘‘silica-silicon’’ foam, which is formed on the surface and in the volume of the boiling silicon at the arc discharge in a local atmosphere with an initial deficiency of available oxygen.

Thus, it is possible to assume that a glowing ‘‘silica-silicon’’ foam material consists mainly of a mixture of: Si (melting point ~ 1414 °C, boiling point ~ 3265 °C) + SiO (melting point > 1700 °C, initial sublimation temperature ~ 1250 °C) + SiO_2 (melting point ~ 1650 (±75) °C, boiling point ~ 2230 °C) + Si_3N_4 (melting point ~ 1900 °C, with subsequent decomposition) + SiO_xN_y, various highly thermostable silicon oxynitrides.

In these circumstances, the gas—frothing agent, foaming the silica-silicon sparks, is apparently gaseous silicon monoxide, SiO.

Theoretically, carbon oxides and tungsten trioxide, WO_3 (melting point ~ 1470 °C, boiling point ~ 1700 °C), produced by the top tungsten or carbon electrodes, could also be suspected as potential frothing agents for the silica-silicon foam.

However within the framework of the experimental geometry described, silicon monoxide appears to be the most probable foaming gas for the silica-silicon sparks.

These burning hot pieces of semiliquid foam are thrown out from the electric arc and then gradually subjected to oxidation keeping a semiliquid state thanks to the thermal flux from the oxidation of suboxidized silicon.

Probably, the heat-resistant crust of these semiliquid foam pieces consists of dioxide, nitride and oxinitride of silicon. The slowed diffusion of oxygen into hot pieces of the silica-silicon foam through this superficial gradually hardening dioxide-oxynitride film guarantees the substantial lifetime of this ball-lightning-like phenomenon. Pieces of gradually oxidable semiliquid foam are slightly similar to the soap froth in your bath, but their superficial hardening film and extremely high temperature easily guarantee an opportunity for their elastic bouncing on a cold firm surface.

At the same time, such pieces of oxidable silica-silicon foam, holding internal heat due to a very low thermal conductivity, can be mechanically disintegrated and then again reunited as long as the internal walls of the foam pieces remain semiliquid. Periodic casual breaks of oxygen through superficial passivating mixed layers of dioxide, nitride and oxinitride of silicon cause local bursts of power flux accompanied with jets and pulsations on the surface of hot liquid foam silicon pieces keeping their sphericity because of the high surface tension of the liquid silicon.

The temperature and pressure of the foaming gas decrease at the end of the process and the hot foam pieces collapse with the formation of aerosol mixture of silicon dioxide, silicon nitride and silicon oxinitride.

It is possible that the next candidates for analogous ball-lightning-like luminous objects could be, for example, plasmatrone-produced pieces of silicon-filled, or carbon-filled, or, for example, the silver powder (frothing agent with boiling point ~ 2162 °C)—aluminium powder (oxidable heat source)—filled alumina (melting point ~ 2054 °C, boiling point ~ 3000 °C) foam heat-insulating material.

Possibly, ‘‘burning foam’’ is the simplest explanation for this extremely interesting experimental phenomenon. Moreover, it seems that the lightning synthesis of the similar hot pieces of slowly oxidable semiliquid foam can also be realized during a thunderstorm, and a part of ball lightning observations can apparently be attributed to observations of such ‘‘burning foam’’ phenomena.

It is even possible to assume that the processes of oxidation in such natural lightning generated pieces of silicon-, metal-, or carbon-filled silicate or aluminosilicate hot foam can be spontaneously converted to the aforesaid alternative electrochemical oxidation of the impregnated reductants inside the hot molten electrolyte foam.

Nevertheless, taking into account some details of the movement and smoke-like behaviour of ball lightning, and especially taking into account some features of the process of initial self-assembly of the ball lightning substance of separate, significantly distant from each other, sparkling elements repeatedly mentioned by the eyewitnesses [2], we believe that it is impossible to explain all the observable characteristics of natural ball lightning within the framework of either ‘‘burning foam’’ or ‘‘burning filamentary aerogel’’ models, without the application of an aerosol model with long-range interacting particles.

Summary

It seems that the proposed model allows us to explain all the observable characteristics of ball lightning, in particular a smoke-like behavior, an ability to keep the form of a ball under conditions of strong atmospheric turbulence, as well as the electromagnetic effects of ball lightning.

This model also explains the great diversity of observable conditions and processes of ball lightning formation. In fact, any reduction-oxidation reaction inside the composite aerosol particles can be proceeded by an electrochemical mechanism under suitable conditions, and a lot of the intra-particle combinations of the three various substances, reductant-electrolyte-oxidizer, are capable of spontaneously forming short-circuited aerosol nanobatteries and the self-assembled ball clouds of these nanobatteries.

The concrete instructions to experimentally simulate the ball lightning phenomenon are strongly dependent on the chosen fuel-reductant and on the method of its atomization, and so they require separate discussion.

In particular, not only the black carbon aerosols, but seemingly also the carbon aerogels, coated with a surface film of molten carbonate electrolytes and heated in an oxidizing atmosphere could be good primary experimental targets to make high-temperature electrochemical aerogel power sources short-circuited by plural surface arc discharges and slightly similar to the aerosol electrochemical generators—ball lightning—described above.

Acknowledgements The author is extremely grateful to Dr. John F. Cooper (Energy Systems, Materials Science and Technology Division Chemistry and Materials Science Directorate, Lawrence Livermore National Laboratory), Dr. Yan Kucherov and Dr. Graham K. Hubler (Materials & Sensors Branch, Naval Research Laboratory) for their useful comments.

References

1. J. Barry, *Ball Lightning and Bead Lightning*. (Plenum Press, New York, 1980)
2. I. Stakhanov, *About Physical Nature of Ball Lightning*. (Energoatomizdat, Moscow, 1985)
3. V.Ya. Aleksandrov, E.M. Golubev, I.V. Podmosheskii, Sov. Phys. Tech. Phys. **27**, 1221 (1983)
4. J. Abrahamson, J. Dinniss, Nature. **403**, 519 (2000)
5. J. Abrahamson, Phil. Trans. Roy. Soc. Lond. **A 360**, 61 (2002)
6. J. Abrahamson, Phys. World. **15**, 22 (2002)
7. J. Cooper, S&TR http://www.llnl.gov/str/June01/Cooper.html (2001)
8. http://www.thrive-metal.com/product1.html (2004)
9. G.S. Paiva et al. Phys. Rev. Lett. **98**, 048501 (2007)

10. O.L. Meshcheryakov, V.A. Salov, V.V. Salov, in *Proceedings of Conference on Visibility, Aerosols and Atmospheric Optics*, ‘‘Instrumentation and Basic Aerosol Properties’’ (2000)
11. O.L. Meshcheryakov, V.A. Salov, V.V. Salov, in *Proceedings of PARTEC 2001, International Congress for Particle Technology*, ‘‘Highly Concentrated Suspensions’’, 168 (2001)
12. C. Govern, I. Spitsberg, B.T. Hazel, http://www.freshpatents.com/Protective-layer-for-barrier- coating-for-silicon-containing-substrate-and-process-for-preparing-same dt20060921ptan2006-0211241.php (2006)