**Filled polyaluminosilicate in LED emitting element design to increase its limit thermoelectric modes**

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**Abstract.** The reliability of a LED lamp is conditioned by the need to increase its service life including the lamp in an inhabited spacecraft. The results of a filled polyaluminosilicate application as a heat-conducting intermediate layer, onto which LED chips are bonded, are considered in the article. The filled polyaluminosilicate application in the LED emitting element design allows increasing its operation temperature due to its specific properties.

1. **Introduction**

Reliability is the most important criterion for microelectronic and spacecraft devices. It is due to reliable materials application operating in a complex combination of force fields and being exposed to corrosive environment, extreme vacuum, and high pressure and temperature.

Highly efficient and reliable light sources are extremely important for interior space lighting in an inhabited spacecraft. Currently, LED light sources having such advantages as a long service life and high light intensity gradually displace the traditional light sources used in various industries. It is LED light sources that meet these requirements. Moreover, LED light sources have the longest service life (more than 80,000 hours) and the highest light output (more than 130 lm/W) compared with all other artificial light devices.

The main requirements for the modern LED engineering market are to reduce energy consumption and to increase luminous flux, service life, and heat removal. One can achieve the mentioned characteristics by using new materials and implementing modern technologies [1-2].

It is known [2] that an increase in a thermoelectric load on a LED intensifies the physicochemical degradation of a semiconductor structure and phosphor composition.

The following degradation mechanisms are known for LEDs and LED emitting elements: a change in the $p$-contact area resistance of a semiconductor structure due to interdiffusion processes and interfacial chemical reactions; mechanical stress relaxation in the semiconductor structure; hydrogen profile redistribution in the semiconductor structure; nitrogen vacancies formation due to Ga-N bonds breaking in the active chip area; indium and magnesium migration in the active semiconductor area; current contraction effect under the ohmic chip contacts; phosphor activator decay (Ce (cerium)) at temperatures above 120 °C.

The work aim is to use the filled polyaluminosilicate with a thermal conductivity of 142 W/m·K in the LED emitting element design to increase its limit thermoelectric operating modes.
The work relevance is due to the ever-increasing requirements for reliability and durability of the structural elements of microelectronics, lighting engineering, and spacecraft devices. In addition, the use of filled polyaluminosilicates in the LED emitting element design and the behavior study of the limit thermoelectric operating modes of LED light sources allow calculating, predicting, and increasing their service life.

A method to remove heat from the emitting element followed by dissipation in the environment with the use of the materials with high thermal conductivity, for example copper or aluminum, is used to manufacture high-power semiconductor emitters. When one develops a semiconductor emission source with the shape close to a filament lamp, it is practically impossible to use a massive radiator, since such a lamp has a closed structure, the so-called filament lamp. It makes it difficult to remove heat from the emitting semiconductor (chip) with subsequent dissipation in the environment. The fact that complicates the situation is that glass, which is a very poor heat conductor, is the main material by means of which the closed volume is created. Therefore, a problem to maximize the heat removal efficiency is very acute. It is known that the LED element operating temperature directly affects its operating mode and service life [3].

The standard filament lamp is a glass bulb, inside of which from four up to eight linears (LED filaments (figure 1)) are located. Twenty eight blue emitting semiconductor chips are located on the linears (in our case, in the LED emitting element design we have used a filled polyaluminosilicate applied on the aluminum base of the LED filament by means of 3D aerosol printing as an adhesive material). To obtain white emission the chips are coated with a layer of the optically transparent sealing polymer material with phosphor powder that converts the portion of blue emission into yellow one. A mixture of blue and yellow emissions produces white emission.

![Figure 1. Dimension drawing of LED emitting element.](image.png)

The space inside the lamp is filled with helium to increase the heat removal efficiency from chips and LED filaments [3].

The temperature effect on the performance and electrical characteristics of the LED emitting element has been studied to determine the possible conditions for the lamp operation.

2. **Experiment**

Experimental Obtainment of LED Filaments.

The AMG-6B aluminum has been chosen as a base material for the LED filament.

A filled polyaluminosilicate with a thermal conductivity of 142 W/m·K has been used as an intermediate dielectric layer to bond chips on the aluminum base. As the intermediate layer basis, the aluminosilicate meets the requirements for heat-resistant and wear-resistant coatings with high thermal...
conductivity provided that its macromolecules form such supramolecular formations, which in their turn form between them (interdomain) hollow areas capable of containing a large number of filler nano and microparticles. As the binder coating component, dendrimer aluminosilicate macromolecules with branched crown formation contain the maximum amount of fillers. The coating is capable of intense heat dissipation released in operating microelectronic and LED devices [1-7].

The developed composite material based on a highly filled dendrimer morphology polyaluminosilicate has been applied on LED linear bases by pneumatic 3D aerosol printing with a 3D printer. The highly filled dendrimer morphology polyaluminosilicate is pre-deagglomerated and placed in an aerosol generator in the Aerosol Jet 15EX printer of Neotech AMT company. The principle of pneumatic aerosol generation from a composite material used for the printer allows applying the dendrimer morphology polyaluminosilicates with various viscosities and the fillers with a wide range of particle size distribution. A working gas (nitrogen or air) is injected into the printer aerosol generator through a narrow hole under pressure to produce aerosol from the composite material. The pressure increase in the aerosol generator causes a rise of the material based on the highly filled dendrimer morphology polyaluminosilicates along the channel, and the aerosol is produced by the gas-material contact. The working gas pressure decreases at the exit from the narrow hole. As a result, a binder based on the dendrimer morphology polyaluminosilicate is sucked into the reduced pressure area through narrow channels from a chamber reservoir of the aerosol generator [8-9].

Primary aerosol formation. After the filled polyaluminosilicate meets a gas stream by the gas jet action, it breaks up into small particles ranging in size from 50 nanometers to 5 microns.

Secondary aerosol formation. The secondary aerosol forms after the primary aerosol particles collide with an obstacle and inhale to form even smaller particles than the primary aerosol ones.

A large proportion of the primary aerosol particles is deposited on the inner walls of the chamber and is drawn back in the aerosol formation. To focus the aerosol jet it is necessary to maintain a distance from the nozzle to the aluminum surface, on which the filled dendrimer morphology polyaluminosilicate material is applied. The distance is from 2 to 15 mm. Such aerosol jet focusing allows applying the composite material at 3D bases. This is carried out by moving the printing head along three axes and by inclining the base along two axes.

28 Ga-N based blue emitting semiconductor chips are regularly located on the undried layer of the filled polyaluminosilicate applied on the aluminum base after the above-described operations. The chip clamping force to the aluminum base is visually controlled. There is no surplus of the material based on the filled polyaluminosilicate because the applied layer thickness is set in advance according to the previously obtained experimental results. After the emitting semiconductor chips have been glued, the obtained devices are exposed to heat treatment in an IR or thermal furnace at a temperature of 70 °C. Drying time is determined by the aluminum base thickness of the LED emitting elements and the number of the applied filled polyaluminosilicate layers. It varies from 15 to 25 minutes.

After the filled polyaluminosilicate drying we bond the chips by ultrasonic microbonding with the iBond5000 digital adjustable microbonding device.

The LED emitting element manufacturing is completed by filling them with a phosphor composition based on a two-component organosiloxane composition with the particles of an yttrium-aluminum garnet that converts the used chip emission into white colour.

3. Results and discussion
Operating (Nominal) Forward Current Determination of LED Emitting Element Samples.

Ten experimental samples of LED emitting elements with different in their chemical nature bases have been chosen for the research. LED chips have been bonded on the samples with various heat-conducting adhesives. Prior to the testing the current-voltage characteristics of the LED emitting elements (figure 2), the luminous flux dependence on the forward current of the LED emitting elements (figure 3), and the luminous efficiency dependence on the forward current (figure 4) have been measured with the Keithley 2410 source meter and FSH-1.0 photometric ball (the measuring range of the luminous flux is from 7 to 3000 lm, measurement inaccuracy is 10%).
Figure 2. Current-voltage characteristic of LED emitting element.

Figure 2 shows that the current-voltage characteristic type of the LED emitting element with all the types of used bases and adhesives corresponds to the type of typical LED characteristic, and the slope is due to series-connected chips.

Figure 3 shows that the dependence type of the luminous flux on the LED emitting element forward current corresponds to the type of typical LED characteristic (for all ten studied samples). The luminous flux stops growing at a forward current of 15 mA.

Figure 3. Luminous flux dependence on forward current of LED emitting element.

Figure 4. Luminous efficiency dependence on LED emitting element forward current.
Figure 4 shows a sharp increase in luminous efficiency at low forward current (2-3) mA. Then a decrease in luminous efficiency, which is linear, is observed. This is also typical for many types of LED emitting elements.

Basing on the dependency result analysis shown in Figures 2-4, we have decided to choose the working (nominal) forward current 10 mA for the experimental samples of LED emitting elements, which is 50% of the electric load margin for the limit forward current 21 mA.

Thermoelectric Load Test

A forward current of 10 mA has been found in the experimental samples of LED emitting elements by the Keithley 2410 source meter. A temperature of 30 °C has been set in the SNOL heat chamber (temperature maintenance range (30-350) °C ± 3 °C). The experimental samples of LED emitting elements have been installed in the heat chamber. The experimental samples of LED emitting elements have been kept in the heat chamber for five minutes for thermal stabilization. Then forward voltage has been measured by the Keithley 2410 source meter. Similarly, the measurements have been taken with increasing temperature in the heat chamber to the value, at which the experimental samples of LED emitting elements have failed. The failure has been fixed by a forward voltage of 0 V, which corresponds to an open electrical circuit. Ten experimental samples of LED emitting elements have been tested. The test results have shown that the limit thermoelectric loads for nine samples have not exceeded 194 °C. This is primarily due to the materials with insufficient thermal characteristics used in the LED emitting element construction to bond chips.

Figure 5 shows the test results of the limit thermoelectric loads for the LED emitting element sample, in the design of which a filled polyaluminosilicate has been used as the adhesive material for chips.

![Figure 5. Forward voltage dependence on LED emitting element temperature.](image)

Figure 5 shows that the forward voltage decreases linearly with increasing temperature, which is typical for LEDs. When the temperature in the heat chamber is 275 °C, there is a sharp increase in the forward voltage from 70 V to 90 V. This process is characterized by a thermal breakdown. When the temperature in the heat chamber is 299 °C, the experimental samples of LED emitting elements fail. Figure 6 shows a photograph of one of the experimental samples of LED emitting elements after testing.

![Figure 6. Tested LED emitting element sample containing filled polyaluminosilicate in its design after thermoelectric load test.](image)

Photo 6 shows mechanical damage to the phosphor composition in the form of a crack. This is due to the loss of the highly elastic state of the organosiloxane binder used to prepare the phosphor composition, as well as the expansion of the LED emitting element supporting structure with increasing
temperature. The crack formation of the phosphor led to a mechanical break in the circuit between chips, which are bonded with a thin gold wire by ultrasound.

4. Conclusion
Basing on the obtained results, one may conclude that the used combination of the base material and intermediate dielectric layer (a filled polyaluminosilicate has been used as the layer) has allowed increasing the temperature, at which the LED emitting element continues operating. This is due to the specific properties of the filled polyaluminosilicate, such as adhesive strength to the base material, thermal linear expansion factor, thermal conductivity, and elastic modulus.

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