

## Active elements of film sources of sound-thermophones

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**Abstract.** The report examines the device and factors affecting the acoustic efficiency of thermoacoustic sound sources – thermophones. Film thermophones are studied, the structure of which is made in the form of a system of layers. Thermophones can be considered as an example of the practical application of films and coatings to ensure the operation of physical instruments. A great importance for the work of thermophones is the quality of the production of thin films, which are their active elements.

### 1. Introduction

For the first time the description of a film thermophone as a generator of sound waves appeared in 1999 [1]. Since then, interest in such sources of sound has not died out. This can be judged, for example, according to the list of references given in [2]. The amplitude-frequency characteristic (AFC) of the film thermophone is uniform over a wide frequency range up to 150 kHz. Such thermophones are the only acoustics generators of sound waves, corresponding to the definition of a piston sound source.

### 2. Research object

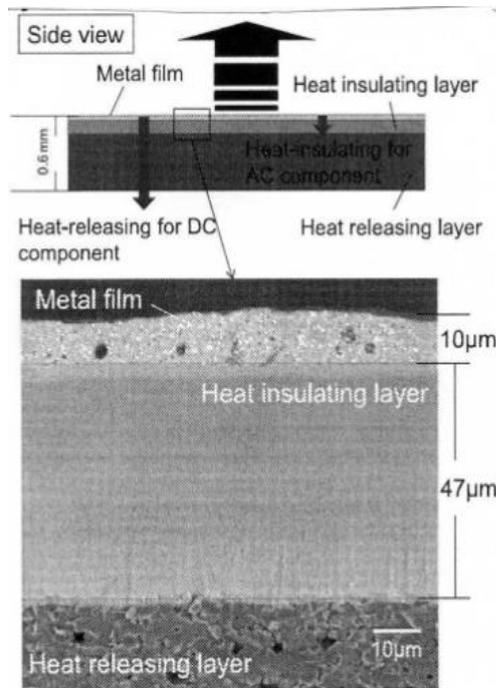
The layered structure of the film thermophone is clearly visible in the cross-sectional image shown in figure 1. This image was obtained by electron microscopy in [3]. Each of the layers has its own functional load. A thin metal film, having a thickness of the order of 10  $\mu\text{m}$ , serves as its active element (AE), the flow of an alternating electric current through which generates sound waves.

In turn, the AE is deposited on the surface of a heat-insulating layer – a substrate having a thickness of 47  $\mu\text{m}$ . The overall mechanical strength and heat dissipation of the stationary heat flux from the AE is provided by a carrier plate having a thickness of 0.6 mm. To produce AE, pure metals, various metal alloys, layers of carbon nanotubes, etc. are used. The thickness  $h_2$  of the AE is usually in the range from 20 nm to 20  $\mu\text{m}$ . To select the thickness of the AE, one can use condition

$$h_2 \leq 0.1\delta'_2 = 0.1\sqrt{2a_1/\omega}, \quad (1)$$

where  $\delta'_2$  is the thickness of the thermal boundary layer in the material of the AE;  $\omega = 2\pi f$  is the frequency;  $a_2 = \chi_2/\rho_2 C_2$  is the thermal diffusivity;  $\rho_2$  is the density and  $C_2$  is the heat capacity of the AE substance. When condition (1) is satisfied, the amplitude of the variable temperature at any point in the volume of the AE synchronously follows the changes in the amplitude of the alternating current flowing through the AE. At high frequencies, when condition (1) is not satisfied, the acoustic efficiency of the thermophone is reduced.





**Figure 1.** Cross-section of the film thermophone.

As a substrate, it is proposed to use a layer of porous silicon. The thicknesses of the substrate  $h_3$  are in the range from 40 to 100  $\mu\text{m}$ . To ensure reliable thermal insulation of the AE, the thickness of the substrate is chosen from the condition

$$h_3 \geq \lambda_{T3} = 2\pi\delta'_3 = 2\pi\sqrt{2a_3/\omega}, \quad (2)$$

where  $\lambda_{T3}$  is the length of the thermal wave and  $a_3 = \chi_3/\rho_3 C_3$  is the thermal diffusivity of the substrate substance. Condition (2) is usually not performed at low frequencies, which leads to a decrease in the levels of sound emitted by the thermophone.

### 3. Thermophone sound radiation

As shown in [4–7], sound emission in a thermophone is provided by two surfaces parallel to each other. The first radiating surface, located at a distance  $x = \lambda_{T1}$ , where  $\lambda_{T1}$  is the length of the thermal wave in the air, from the AE surface and generates a traveling acoustic wave  $p_1$  due to the thermoacoustic effect. In addition, the substance of a solid body, on whose surface the AE is applied, is affected by a variable heat flux. This leads to the appearance of mechanical vibrations of the free surface of the body due to the thermal expansion of the substance and, as a consequence, to the radiation of the traveling sound wave  $p_3$ , from the surface of the AE ( $x = 0$ ). The central axes of the combined sound sources coincide, the total amplitude of the sound pressure at the point  $x$  on the central axis of the thermophone is given by

$$p(x) = p_1(x) + p_3(x) = 2U_{01}\rho_1 c_1 \left| \sin\left(\frac{k\alpha_1}{2}\right) \right| + 2U_{03}\rho_1 c_1 \left| \sin\left(\frac{k\alpha_3}{2}\right) \right|, \quad (3)$$

where  $\alpha_1 = \sqrt{(x - \lambda_{T1})^2 + r_0^2} - x$ ;  $\alpha_3 = \sqrt{x^2 + r_0^2} - x$ ;  $r_0$  is the equivalent radius of the radiating surface;  $\rho_1$  is the density;  $c_1$  is the speed of sound in the air and  $k = \omega/c_1$  is the wave number.

The formulas for calculating the amplitudes of the vibrational velocities entering into expression (3) have the form, here,  $a_1$  is the thermal diffusivity of the gas;  $U_{01} = \sqrt{a_1 \omega} \beta_{V1} T'_m$ ;  $U_{03} = \sqrt{a_3 \omega} \beta_{V3} T'_m$ , where  $a_1$  is the coefficient of thermal volumetric expansion of the gas;  $T'_m$  is the amplitude of the

variable temperature of the AE;  $\beta_{V3} = 3\alpha_{L3}$ ;  $\alpha_{L3}$  is the coefficient of thermal linear expansion of the substrate substance. To calculate the amplitude of the variable temperature of the AE surface, one can use the following expression [6]

$$T'_m = \frac{q_e}{\sqrt{\omega(K_{H1} + K_{H3})^2 + (\omega\varepsilon)^2}}, \quad (4)$$

where  $q_e = p_e/S$  is the specific peak power of heat release AE;  $p_e = R_e I_m^2$  – power consumed by the thermophone;  $R_e$  – total electrical resistance of the AE;  $I_m$  is the amplitude of the alternating current;  $S$  is the surface area of the AE;  $K_{H1} = \sqrt{\chi_1 \rho_1 C_{p1}}$ ;  $K_{H3} = \sqrt{\chi_3 \rho_3 C_{p3}}$ ;  $\varepsilon$  is the heat capacity per unit area of the AE of thickness  $h$ .

The main difficulty that arises in the calculation of thermophones is the lack of data on the physical parameters of the AE substance and the substrate. Table values of these parameters, available in the literature, are not suitable for this purpose, since they change in thin layers due to dimensional effects. We show that the physical system studied by us makes it possible to obtain experimentally the values of the parameters necessary for carrying out the calculations. To do this, we turn to expression (4). Film thermophones operate in a wide frequency band, and this allows us to distinguish between low-frequency and high-frequency excitation modes of thermophones. At low frequencies, the inequality  $\omega(K_{H1} + K_{H3})^2 \gg (\omega\varepsilon)^2$  is satisfied. Formula (4) is simplified and takes the form

$$T'_m = q_e / \sqrt{\omega(K_{H1} + K_{H3})}. \quad (5)$$

At high frequencies, the inequality  $\omega(K_{H1} + K_{H3})^2 \ll (\omega\varepsilon)^2$  is fulfilled and, consequently, we have

$$T'_m = q_e / \omega\varepsilon. \quad (6)$$

#### 4. Conclusion

If formulas (5) and (6) are used to calculate the sound pressure (3), then we obtain the linear dependences  $p(p_e)$ . The magnitude of the sound pressure amplitude can be measured quite accurately with modern microphones. This allows using the simplest calculations to obtain the parameter  $(K_{H1} + K_{H3})$  at low frequencies, and  $\varepsilon$  at high frequencies. This method was used by us in [5, 7] to determine the value of the parameter  $K_{H3}$  of laminated plastics. Given the unique technical characteristics of film thermophones, it can be argued that they can be used as sound sources, both for conducting scientific research, and for creating technical devices for various purposes. Reported features of the work of thermophones can be used to create acoustic methods for measuring certain thermophysical parameters of a substance.

#### References

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