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Physical mechanism of helium detection in the Pirani vacuum sensor

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A physical mechanism is proposed that describes the operation of a Pirani-type vacuum sensor in a helium atmosphere and in helium-air mixtures. It is shown that the cooling rate of the heater in the Pirani sensor is determined by the heat removal by helium atoms desorbed from the metal surface, and helium atoms carry away significantly more heat from the surface than chemisorbed molecules of atmospheric gases. In the case of helium-air mixtures, there is competition between helium atoms and molecules of atmospheric gases for adsorption sites, leading to a significant change in the temperature of the heater.

Keywords: helium, atmospheric gases, vacuum measurement, Pirani sensor.

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Vacuum thermoelectric sensors suggested in the beginning of XX century by M. Pirani [1], remain the most widely used device to measure pressures in range 10^3-10^{-3} mbar, i.e. in area of „low“ vacuum [2,3]. They are also widely used as „thermal conductivity sensors“ of gas ensuring detection of gas composition changes to solve various analytical and industrial objectives [4].

Besides, even in the beginning of last century it was obvious that operation of such type sensors is determined not by thermal conductivity of gas, which with good accuracy does not depend on pressure [5], but by mechanisms of heat removal from a heater surface. Until now the mechanism of such process was unknown, and for its description an „accommodation coefficient“ was used, which did not have physical explanation and was introduced in Hertz–Knudsen formula to match it with measured data only.

In our recent paper [6] the mechanism was suggested based on laws of adsorption-desorption equilibrium of the atmospheric gases on surface of metal heaters. It permits rather correct description of operation of the thermoelectric sensor in contact with the atmospheric gases. But even minor admixture of helium also greatly distorts the measurement results.

This paper objective is a review of the molecular mechanism which would describe the laws of Pirani sensor operation in atmosphere of helium and helium-air mixtures in wide range of pressures and electrophysical parameters of the sensor.

Experiments were performed on vacuum sensor TEKHNAN VV 2, in which the low vacuum measurements in Pirani mode and high vacuum measurements in Bayard–Alpert mode were implemented on same heating device — iridium cathode activated by yttrium oxide. Length of the wire heater was 50 mm, its diameter was 100 μm. Some experiments were performed in home-made experimental set-up, where different metals were used as heater material: tungsten, molybdenum, and rhenium.

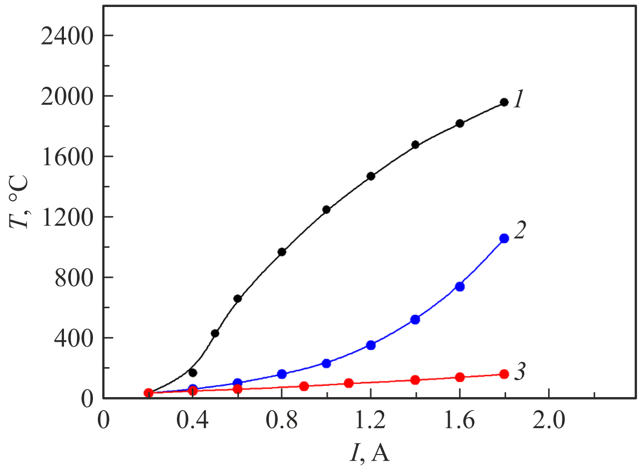

Figure 1. Temperature change of iridium-yttrium cathode vs. filament current. 1 — vacuum ($p < 10^{-3}$ mbar), 2 — air ($p = 1000$ mbar), 3 — He ($p = 1000$ mbar).

Heaters temperature in the sensor was determined using a standard formula

$$R_t = R_0(1 + \alpha t),$$

for iridium $\alpha = 4.0 \cdot 10^{-3}\,{}^\circ\mathrm{C}^{-1}$ [7]. In pyrometric area the measurement data are well agreed with the temperature determined by micropyrometer.

Fig. 1 shows temperatures of iridium-yttrium heaters vs. filament current: curve 1 was measured in vacuum $p = 10^{-3} \cdot 10^{-7}$ mbar (do not depend on pressure); curve 2 — in air atmosphere $p = 1000$ mbar, curve 3 — in helium atmosphere $p_{\mathrm{He}} = 1000$ mbar. It is obvious that air or helium supply decrease the filament temperature, at wherein helium cools the filament much stronger.

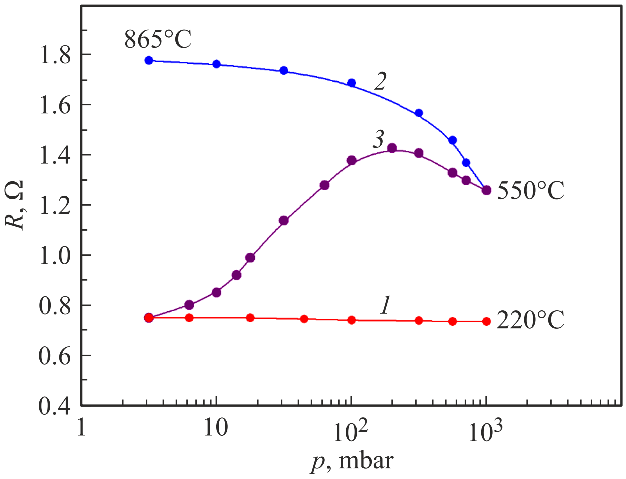

Figure 2. Resistance change of iridium-yttrium cathode vs. gas pressure in chamber for $I = 1.4$ A. *1* — only helium, *2* — only air, *3* — helium supply to $p = 4$ mbar and then air supply to $p = 1000$ mbar.

Replacement of iridium-yttrium heater by molybdenum or tungsten filaments, iridium or rhenium tapes also confirms rather strong cooling of heaters in helium atmosphere.

Dependence of heater resistance on pressure of air or helium in chamber for all used materials in case of $I = \text{const}$ has complex *Z*-like form. At that in pressures range $10-10^{-1}$ mbar an evident dependence of heater temperature on gas pressure is observed. And vice versa, at extreme low and high pressures this dependence is low [6]. For example, in case of helium in range of pressure changes from 1–4 to 1000 mbar a plateau is observed (curve *1* in Fig. 2). For comparison a similar graph is shown for air (curve *2* in Fig. 2), where this dependence is more obvious.

Joint supply of air and helium results in rather interesting results, which explain the physical pattern of processes on surface of cathodes upon their contact with gas. Initially helium was supplied to pressure $p_{\mathrm{He}} = 4$ mbar, then air was added by doses such that total pressure increased. It is seen that air addition to helium reduces the heater cooling efficiency, and heater temperature increases (curve *3* in Fig. 2). But helium contribution is neutralized in full only when its concentration is below 0.4% of concentration of atmospheric gas molecules, i.e. during supply up to atmospheric pressure.

In case of atmospheric atoms the heat removal from the metal heater is ensured by molecules chemisorbed on surface ($N_2, O_2, \ldots$) with low binding energy $E \approx 0.5$ eV. Note that are replacement by pure nitrogen (99.9%) did not change the test results. As paper [6] shows at pressure increasing to 10–1000 mbar the heat exchange gas–substrate is low dependent on pressure of nitrogen (air). Under such conditions the chemisorbed molecular layer is filled, and heat exchange gas–substrate is determined by life time of chemisorbed nitrogen molecule on surface, which depends on temperature only (Fig. 3, *a*).

If only helium is supplied the same situation is observed: at pressures He $\geq 1-4$ mbar the layer of adsorbed helium atoms saturates (Fig. 3, *b*), and heat exchange between the cathode and gas id determined not by external pressure, but by life time of helium atom on heater surface. Thus in dependence of heater resistance on pressure the plateau is observed (curve *1* in Fig. 2), although the pressure changes by 250 times.

In case of joint supply of nitrogen and helium their competition occurs on surface (Fig. 3, *c*). Fig. 2 shows that initially at same pressures of air and helium (about 4 mbar) the helium makes main contribution to cooling. In final point at pressures of air close to the atmospheric pressure the helium contribution is absent: apparently, molecules of the atmospheric gases displace the helium atoms from surface, and it completely „gets out of a game".

Let's make some estimates relating to adsorption–desorption properties of helium. At $p_{\mathrm{He}} = 1$ mbar the dependence $R = f(p_{\mathrm{He}})$ practically reaches the plateau (curve *1* in Fig. 2). Let's use known expression for flux density ν of gas molecules on surface

$$\nu = p(2\pi mkT)^{-1/2},$$

where k — Boltzmann constant, m — molecule (atom) mass, p — gas pressure. Knowing surface area of heater we can calculate the flux of helium atoms dropping on it.

The calculated flux is $\upsilon' = 1.9 \cdot 10^{20}\,\mathrm{s}^{-1}$; this flux „extinguishes" filament temperature to $T = 220°\mathrm{C} = 493$ K. Supposing that all supplied He atoms are accommodated equally, this flux will „carry away" from surface power

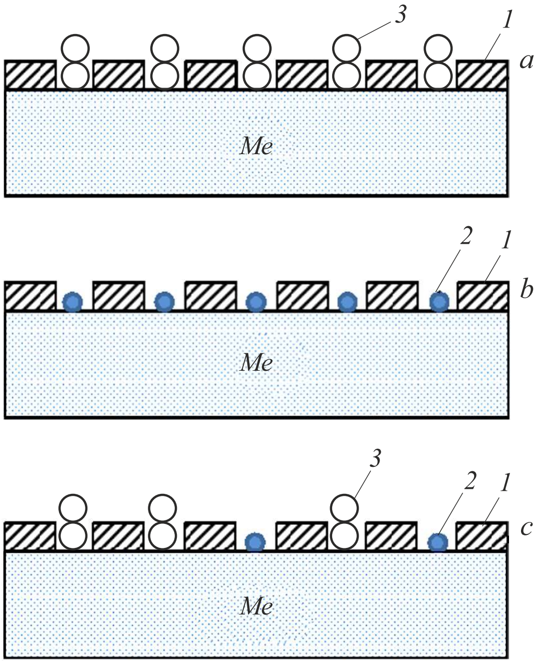

Figure 3. Simplified illustration of processes on surface of metal for gas mixture of nitrogen and helium. *1* — chemisorbed layer of nitrogen atoms, not involved in heat exchange; *2* — helium atoms; *3* — nitrogen molecules.

$P_{\text{He}} = v'kT = 1.3\,\text{W}$. At the same time power allocated to filament is $P_f = I^2R = 1.47\,\text{W}$. So, our estimates show that heat equilibrium $P_{\text{He}} \approx P_f$ is ensured by flux of He atoms, at that at $p_{\text{He}} = 1\,\text{mbar}$ practically all He atoms participate in heat exchange with full heat accommodation. If we suppose that concentration of He atoms on surface is $N \approx 10^{14}\,\text{cm}^{-2}$, then life time of helium atom at $T = 493\,\text{K}$ will be $\tau = N/\nu \approx 5 \cdot 10^{-7}\,\text{s}$.

Let's consider the situation during joint adsorption of nitrogen and helium. Using value of desorption energy of chemisorbed nitrogen molecules from surface of metals (Ir, W, Mo) $E \approx 0.5\,\text{eV}$ [8] we estimate the life time of nitrogen molecules in relation to desorption at same temperature $T = 493\,\text{K}$, for which estimation of life time of helium atoms was given above. using Frenkel's formula [9] and taking pre-exponential factor $\tau_0 = 10^{-13}\,\text{s}$, we obtain the life time of nitrogen $\tau \approx 10^{-7}{-}10^{-8}\,\text{s}$. We can say that in first approximation the life times of helium atoms and nitrogen molecules are close to each other. So, upon further significant increase in nitrogen pressure in chamber as result of competition the physisorbed helium atoms will be displaced by chemisorbed nitrogen molecules having relatively high binding energy. Note that all described above processes do not relate to bulk thermal conductivity of helium, but relate to its sorption-desorption characteristics only.

So, the consistent physical mechanism is suggested, which associates the known sorption-desorption properties of helium with effects observed in Pirani sensor. Processes occurred during measurement of helium-air mixtures, are determined by mechanism of adsorbates competition on surface. This mechanism can be used also to describe the sensors operation with other gases, such as neon or methane.

Conflict of interest

The authors declare that they have no conflict of interest.

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