HEAT EXCHANGE BETWEEN A SUBSTRATE AND SUBSTRATE HOLDER IN THERMAL CONTACT

V. K. Samoilikov

The article presents the results of an experimental investigation of high-temperature contact heat exchange between the polished surface of a substrate and the rough surface of a substrate holder under various conditions of contact between them in different gas media, under vacuum, and at different gas flow rates.

Introduction. The processes of chemical deposition of monocrystalline layers of semiconducting materials from the gas phase onto monocrystalline substrates are among the basic processes in the production of active elements of integrated circuits.

Substrates are mounted in a polyhedral prismatic substrate holder heated in a reaction chamber to operating temperature. The uniformity of the substrate temperature, which is determined by the conditions of its contact with the substrate holder surface, ensures that high-quality structures are formed in the deposited layer.

The reliability of thermal contact between contacting items can be ensured by increased specific loads or by materials (adhesives, pastes, mastics) that fill the gap between them and have a relatively high thermal conductivity coefficient [1].

However, the extremely high requirements to the cleanliness of semiconductor fabrication and the low mechanical strength of the substrate material preclude the above-mentioned recommendations. This was the reason for the carrying out the present investigation.

Investigation Procedure. We consider one of the typical cases of mounting of substrates on a substrate holder, when thermal contact between them is ensured by the weight of the substrate itself. For example, a silicon substrate of thickness $d_s = 0.4 \text{ mm}$ and diameter $d_s = 100 \text{ mm}$ weighs about $8 \text{ g}$.

A diagram of thermal contact between a substrate and its holder and the temperature variation in the "substrate holder-substrate-wall of reaction chamber" system are presented in Fig. 1. The same figure (at the left) also shows (in scale) a fragment of the recorded surface waviness of a typical substrate holder.

The roughness of the substrate holder surface and the waviness of the substrate lead to the appearance of a gap between them $\Delta$ whose thickness is much smaller than the substrate diameter $d_s$, i.e., $d_s \gg \Delta$.

Let us set up a heat balance equation for the system analyzed. The heat flux supplied from the holder to the substrate is

$$q_1 = q_{r1} + q_{tg} + q_{tdc}.$$  \hspace{1cm} (1)

The heat flux transferred by the substrate to the reaction chamber walls is

$$q_2 = q_{r2} + q_c.$$  \hspace{1cm} (2)

Let us write expressions for the heat fluxes in terms of their components:

$$q_{r1} = \alpha_r (T_{sh} - T_{s1}) = \varepsilon_{red1} 0.07 \left[ \left( \frac{T_{sh}}{100} \right)^4 - \left( \frac{T_{s1}}{100} \right)^4 \right],$$  \hspace{1cm} (3)
\[ q_{lg} = \left( \frac{\lambda_g}{\Delta_g} \right) (T_{sh} - T_s) , \]  \hspace{1cm} (4) \\
\[ q_{ldc} = \left( \frac{\lambda_{sh}}{\Delta_{dc}} \right) (T_{sh} - T_{s1}) , \]  \hspace{1cm} (5) \\
\[ q_{r2} = \alpha_{r2} (T_{s2} - T_w) = \epsilon_{red2} \sigma_0 \left[ \left( \frac{T_{s2}}{100} \right)^4 - \left( \frac{T_w}{100} \right)^4 \right] , \]  \hspace{1cm} (6) \\
\[ q_c = \alpha_c (T_{s2} - \bar{T}_g) . \]  \hspace{1cm} (7) 

Here \( \epsilon_{red1} \) and \( \epsilon_{red2} \) are the reduced emissivities of the systems: "substrate holder–substrate" (system 1) and "substrate–reaction chamber wall" (system 2), respectively; \( T_{sh}, T_{s1}, T_{s2}, T_w \) are the temperatures of the substrate holder, of the side of the substrate facing the holder, of the side of the substrate facing the reaction chamber wall, and of the reaction chamber wall; \( \bar{T}_g \) is the mean temperature of the gas contained between the substrate and the reaction chamber wall; \( \lambda_g \) and \( \lambda_{sh} \) are the thermal conductivity coefficients of the gas and of the substrate holder material, respectively; \( \sigma_0 = 5.67 \cdot 10^{-8} \text{ W/m}^2\text{K}^4 \) is the Stefan–Boltzmann constant; \( \alpha_{r1}, \alpha_{r2}, \alpha_c \) are the radiative heat transfer coefficients of systems 1 and 2, and the coefficient of heat transfer by convection from the substrate to the gas flow, respectively.

The radiative heat transfer coefficient of system 1 is
\[ \alpha_{r1} = \epsilon_{red1} \sigma_0 \left( T_{sh}^3 + T_{sh} T_{s1}^2 + T_{sh} T_{s1}^2 + T_{s1}^3 \right) . \]  \hspace{1cm} (8)

The reduced emissivity \( \epsilon_{red1} \) can be determined from the expression for a system of plane-parallel bodies, since
\[ \epsilon_{red1} = \frac{1}{\epsilon_s \epsilon_{sh}} - 1 . \]  \hspace{1cm} (9)

Since for the substrate the number \( Bi << 1 \), then with an accuracy sufficient for calculation we may write
\[ T_{s1} \approx T_{s2} = T_s . \]

The substitution of Eqs. (3)–(5) into Eq. (1) on the assumption that the resulting heat flux components do not influence one another, leads to the equation
\[ q_1 = \left[ \alpha_{r1} + \left( \frac{\lambda_g}{\Delta_g} \right) + \left( \frac{\lambda_{sh}}{\Delta_{dc}} \right) \right] (T_{sh} - T_s) = \frac{1}{R_1} (T_{sh} - T_s) . \]  \hspace{1cm} (10)

The substitution of Eqs. (6) and (7) into Eq. (2) yields
\[ q_2 = (\alpha_{r2} + \alpha_c) (T_s - T_w) = \frac{1}{R_2} (T_s - T_w) . \]  \hspace{1cm} (11)

Under the conditions of a steady-state heat regime the following equality holds
\[ q_1 = q_2 = q_{res} . \]  \hspace{1cm} (12)