FORCE OF ATTRACTION BETWEEN SOLIDS WITH DIFFERENT TEMPERATURES

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The methods of fluctuation electrodynamics based on the theory of molecular Van der Waals forces are used to obtain an expression for the density of attraction force between two absorbing media with different temperatures, which are separated by a nonabsorbing plane-parallel layer. The spectral density of the force was calculated as a projection of the Maxwell stress tensor on the outer normal to the solid surface. The mean square characteristics of the fluctuation field of the solids are obtained using the generalized Kirchhoff’s law and Green’s function of the corresponding regular problem. The solution versions are obtained depending on the relation between the temperatures of interacting solids. It is shown that for equal temperatures of the solids the expression obtained yields the formula for the attraction force in the case of equilibrium.

1. INTRODUCTION

The theory of the force of interaction between two atoms that have no constant dipole moment was developed in [1, 2]. The presence of a force attraction between neutral particles leads to appearance of such forces between two solids separated by a very small gap. A macroscopic theory of molecular forces of attraction between solids separated by a vacuum gap or a nonabsorbing medium is proposed in [3]. According to the main idea of this theory, the interaction between solids occurs via a fluctuational electromagnetic field, which is always present inside any absorbing medium and extends outside as thermal radiation and the near quasistatic field. The author of the theory studies the interaction between solids in the form of two media that fill halfspaces with plane-parallel boundaries separated by a certain distance and calculates the spectral density of the force of attraction by solving an inhomogeneous boundary-value problem with the corresponding boundary conditions and external random sources distributed in two media. The solution has complete generality and can be applied to any media at any temperature and, moreover, in the limiting case of rarefied media we obtain the known laws of interaction for individual atoms. The same result was obtained in monograph [4] on the basis of the generalized Kirchhoff formula, the complex Lorentz lemma, and the known Green’s function of the regular diffraction problem for a point source located in the plane nonabsorbing gap between two absorbing homogeneous and isotropic media. The general theory of Van der Waals forces developed using the methods of quantum field theory is presented in [5]. The results of this theory can be used for determining the forces that act between two solids separated by an absorbing layer, such that the formulas obtained in [3] are changed only insignificantly. It is of interest that depending on the relation between the permittivities of all of the three media both attraction and repulsion are possible. It must be noted that in the above papers we considered the case of equilibrium in which the temperature of all of the media that take part in the force interaction is the same.

The first experimental measurements of the force of attraction between two plane-parallel plates separated by a gap of order of 10^{-6} m [6] are in fair agreement with the theory developed. Further checking of the theoretical results conducted experimentally in [7-9] also demonstrated fair qualitative and quantitative agreement between the theory and experiment.

Today, in view of the development of the methods of probe microscopy and physics of microcontacts, study of the interaction between solids via thermal fluctuation fields acquires new meaning and stimulus.
In particular, extensive use of probe microscopes for the study and local modification of properties of the surface of condensed media [10, 11] resulted in problems in which we must consider the pondermotive interaction and the energy exchange between the needle and the sample the temperatures of which are different.

In this paper, by calculating the spectral components of the Maxwell stress tensor, we obtain an expression for the density of the force of attraction between two arbitrary absorbing media, which are separated by a nonabsorbing plane-parallel layer and heated to different temperatures. We consider the limiting cases in which the temperature of one medium is much greater than that of the other and it is also shown that for equal temperatures the expression for the force is identical to the formulas for the case of equilibrium.

2. FORMULATION OF THE PROBLEM

The electrodynamic theory of thermal fluctuations provides a method for detailed study of the structure and properties of fluctuational electromagnetic fields of heated solids. These are, for example, the spectral intensities of electric and magnetic energies, Poynting's vectors, and Maxwell stresses. The statistical averages of bilinear forms, i.e., different correlation functions or spectral intensities of fluctuations, can be found by solving a standard boundary-value problem of electrodynamics and using the electrodynamic fluctuation dissipation theorem (FDT) for correlation functions of random currents distributed over the entire volume of an absorbing medium.

The second moments of spectral amplitudes of the fluctuation field can be found in another manner using their relation to the thermal losses of the diffraction field of point sources from the formulas that generalize the classical Kirchhoff equation [4]

\[ \pm A_{\Omega}(\vec{r}_1)B_{\Omega}(\vec{r}_2) = \frac{2}{\pi} \Theta(\omega, T)Q_{AB^*}(\vec{r}_1, \vec{r}_2; \vec{r}_2, \vec{r}_2), \]  

where \( A_{\Omega} \) and \( B_{\Omega} \) are two intensity components chosen out of six intensity components \( \vec{E} \) and \( \vec{H} \) of the thermal field along the orientations \( \vec{r}_1 \) and \( \vec{r}_2 \) of the point sources, \( \Theta(\omega, T) = (\hbar\omega/2) \coth(\hbar\omega/2kT) \) is the average energy of the oscillator at temperature \( T \), and \( Q_{AB^*} \) are the combined thermal losses of the diffraction field of the point sources in the solid under study located at the points \( \vec{r}_1 \) and \( \vec{r}_2 \). The plus corresponds to two electric or two magnetic components and the minus corresponds to electric and magnetic components. The asterisk denotes complex conjugation. Evidently, finding the Green's function of the regular problem is a simpler process in a number of cases.

Knowing the second moments of the spectral amplitudes of the fluctuational field between two solids, we find the density of the force acting on the solids by integrating with respect to all frequencies of the spectral component of projection of the Maxwell stress tensor onto the direction of a unit normal to the surface chosen. The spectral density of this tensor with respect to positive frequencies at a certain point \( \vec{r} \) is

\[ T_{\omega\beta}(\vec{r}) = \frac{1}{8\pi} \left\{ \frac{2E_{\alpha}(\omega, \vec{r})D_{\beta}(\omega, \vec{r}) - \vec{E}(\omega, \vec{r})\vec{D}^*(\omega, \vec{r})\delta_{\alpha\beta} + c.c.}{\Theta(\omega, T)} \right\} + \frac{1}{8\pi} \left\{ \frac{2H_{\alpha}(\omega, \vec{r})B_{\beta}(\omega, \vec{r}) - \vec{H}(\omega, \vec{r})\vec{B}^*(\omega, \vec{r})\delta_{\alpha\beta} + c.c.}{\Theta(\omega, T)} \right\}, \]

where the series

\[ \vec{E}(t, \vec{r}) = \int_{-\infty}^{\infty} \vec{E}(\omega, \vec{r})\exp(i\omega t)\,d\omega \]

is used for the real stationary fields and, by analogy, for the field \( \vec{H} \) and inductions \( \vec{D} \) and \( \vec{B} \).