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ABSTRACT

Here, we discuss possible applications of the Casimir forces in micro- and nanosystems. The main part of this paper is devoted to actuation with quantum fluctuations and to the relative contribution of van der Waals and Casimir interactions to adhesion. Switching between the amorphous and crystalline states of phase change materials could generate force contrast sufficient for actuation, though for practical applications, the influence of protective capping layers and volume compression have to be better understood. Resilience against the pull-in instability is also a critical point defined by the material choice, dissipation in the system, and roughness of the surfaces. The adhesion induced by the Casimir forces is omnipresent, and it can play a pivotal role in unwanted stiction demanding deeper understanding. The open problems are the distance upon contact and the relative area of the real contact since both of them control the adhesion. An experiment designed to answer these questions is briefly discussed.

Quantum fluctuations of the electromagnetic field generate forces between uncharged bodies in vacuum or in a medium. Historically, these forces at distances below a few nanometers are called van der Waals (vdW) forces, where the gecko lizard is a magnificent example in nature,[1] but at larger separations (e.g., above 20 nm), when retardation becomes important, the same forces are termed as Casimir forces (CFs) after Casimir,[2] who was the first to recognize the relation of the forces to the zero-point energy. Soon after, Lifshitz and co-workers[3,4] proposed a general macroscopic theory describing the forces via the dielectric responses of the bodies and intervening medium, as well as explained common origin of the vdW and Casimir forces. Sometimes, the common name dispersion forces is also used. The dependence of the CF on material optical properties is an important outcome of the Lifshitz theory and, in principle, can be used to tailor the performance of actuating devices.

At short distances, the vdW forces together with the electrostatic forces play an important role in wetting phenomena, lipid bilayers, and colloid and interface science in general.[5,6] These forces made the basis for the seminal Derjaguin–Landau–Verwey–Overbeek (DLVO) theory.[7,8] At larger distances, the dispersion forces fade away relatively fast and seemingly do not play a significant role in applications. In the essentially retarded regime, for separations typically above 200 nm, the interest to the CF is mostly fundamental in search of new forces.[9] However, there is a multitude of directions where the application of the CF is attracting strong interest. These are applications in micro/nanoelectromechanical systems (MEMS/NEMS)[10–14] and application of MEMS to measure the forces,[15,16] biological systems (gecko, lipid membranes),[1,17] and adhesion between rough surfaces.[18,19]

Furthermore, serious effort was directed toward systems with repulsive interaction, which could pave the way toward Casimir levitation minimizing static friction.[10] The repulsion occurs when solids are separated by a liquid, which has the dielectric function (at imaginary frequencies) in between those of the solids. This is a rare combination of the materials since typically solids are denser optically than liquids. Nevertheless, repulsion was observed experimentally between Au and silica immersed in bromobenzene,[20] although the effect was rather weak. The repulsion can be used to develop very sensitive force or torque sensors where objects can be freely translated or rotated above the substrate. The first example of such a system has been realized recently[21] where the Casimir torque was observed between a birefringent crystal and a liquid crystal separated by a distance of 20 nm.

Attempts to generate Casimir repulsion in vacuum (or gas) were less successful though from the technology point of view, this configuration is more preferable than a liquid gap. All solid non-magnetic materials are attracted in vacuum because vacuum has the lowest dielectric function. In principle, materials with electric permittivity and magnetic permeability could lead to repulsion,[22] but no natural materials with a non-vanishing magnetic susceptibility in the range of relevant optical frequencies exist.[23] It was expected that metamaterials could provide the repulsion,[24] but calculations for different artificial materials (especially chiral metamaterials[25]) demonstrated that the effect is too weak.[26] Topological insulators are an additional class of materials, which are able to demonstrate the Casimir repulsion in vacuum[27,28] due to competition between bulk and surface contributions. The latter is related to the Hall conductivity. A series of interesting effects can also be realized for 2D materials[29] (also see a review in Ref. 30). However, although the repulsion in vacuum is actively investigated theoretically, still there are no experimental realizations of the theoretical ideas.

The other perspective application of the CF is the actuation of micro and nanodevices with quantum fluctuations. This application is very natural because all modern methods to measure the CF[9] use MEMS, for which the force is balanced by an elastic spring (AFM cantilever or torsional rod). The CF has a profound influence on oscillatory behavior of microstructures when two surfaces are separated by the distances smaller or of the order of 100 nm.[31] However, to provide actuation, a mechanical movement of one of the bodies by external forces is assumed. For many applications, it is interesting to exclude this movement and control the process with fields.

A clever realization of this idea was demonstrated in Ref. 32, where the force was modulated by exciting charge carriers in a low-doped silicon wafer by laser light. Due to a specific dependence of the force on the optical properties of the material, variation of Si conductivity from the dielectric to metallic state resulted in the force modulation of only 1%. The force contrast up to 50% was measured between the gold sphere and a plate covered with Au or Indium Tin Oxide (ITO)[33] due to a significant difference between the optical properties of Au and ITO. However, to switch between the forces in this system, one has to make the mechanical movement. To exclude this movement, a phase change material (PCM) was proposed since its dielectric function strongly varies when the material is switched from the amorphous to the crystalline state. For a PCM AIST (Ag–In–Sb–Te) system, a force contrast up to 20% was observed between two phases.[34]

The adhesion between rough surfaces is a natural phenomenon that can be controlled by the CF. Strong adhesion due to chemical interaction or capillary forces can be excluded by special preparation of the surfaces, but the adhesion owing to the dispersion forces is omnipresent and cannot be excluded. It is responsible for phenomena such as a firm grip of geckos on walls,[1] stiction of polymeric films to solids,[35] or malfunction of MEMS devices induced by stiction of separate elements.[36] Two rough surfaces come into contact with each other at a number of points with the area of contact being small in comparison to the nominal area of adhesion. It can happen that much weaker retarded interaction can be more important for the adhesion than stronger vdW interaction acting near the contact. This situation was observed experimentally using adhered cantilevers with different roughnesses.[18] The detailed understanding of the forces acting between adhered rough surfaces will allow us to control unwanted adhesion in MEMS fabrication and operation and will give contribution to understanding of friction.[37]

In this paper, we explain in more detail recent developments and open questions in actuation of electromechanical systems with the CF and adhesion between rough surfaces.

The dependence of the CF on interacting materials allows one to tailor the force that can be used as a new concept in actuation dynamics of MEMS/NEMS. Typical elements of such systems are micro-switches [e.g., Fig. 1(a)], which are basic components of vibration sensors, accelerometers, etc. The development of increasingly complex MEMS will attribute much attention to scaling issues as this technology evolves toward NEMS. With this trend, the Casimir interaction inevitably has to be faced since separate elements of these systems have large enough areas but the distance between them is small enough for the forces to be operative. To see this, we can compare the largest electrostatic pressure between parallel metallic plates with the CF at small separations. For the largest electric field that is the breakdown field $E_b \approx 3 \times 10^6$ V/m, the electrostatic pressure is $P_{el} = \varepsilon_0 E_b^2/2 \approx 40$ Pa, where ε_0 is the permittivity of vacuum. The Casimir pressure is $P_C = \eta(d)\pi^2 \hbar c/240 d^4$, where $\eta(d)$ is the reduction factor describing deviation of the materials from ideal metal.[38] The Casimir pressure between two gold plates exceeds the largest electrostatic pressure at distances $d \leq 58$ nm (the reduction factor $\eta(58\,\text{nm}) \approx 0.34$).

The equilibrium CF[4] is defined by the material dielectric functions $\varepsilon(i\zeta)$ at imaginary frequencies $\omega = i\zeta$. Owing to the Kramers–Kronig relation,

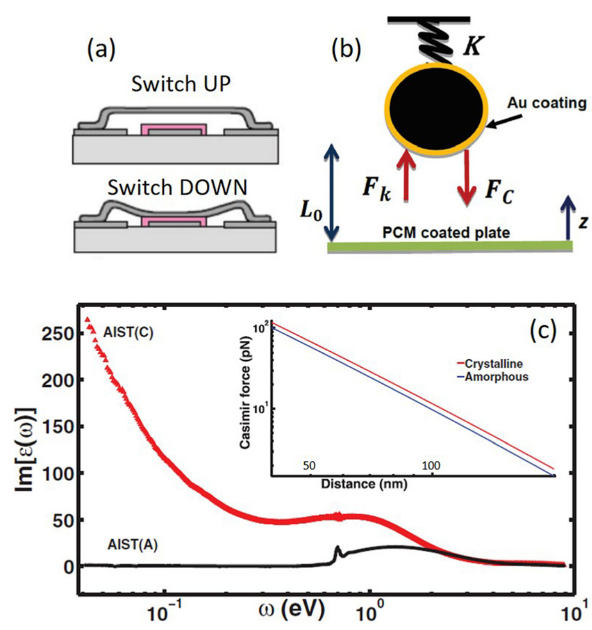

FIG. 1. (a) Schematic presentation of a microswitch. (b) Schematic of experimental realization of a PCM-based microdevice actuated by the CF with an initial separation L_0. (c) Imaginary part of the dielectric function of PCM AIST measured by ellipsometry for amorphous (A) and crystalline (C) phases. The inset demonstrates the measured force vs distance for these two phases.

$$\varepsilon(i\zeta) = 1 + (2/\pi)\int_0^\infty d\omega\omega\varepsilon''(\omega)/(\omega^2+\zeta^2), \quad (1)$$

where $\varepsilon''(\omega)$ is the imaginary part of the dielectric function. This means that a wideband of real frequencies ω contributes to the force. Therefore, to get significantly different forces, the materials must have significantly different $\varepsilon(i\zeta)$. For example, the force contrast between intrinsic and degenerate Si is only 1% (Ref. 39) although the dielectric functions differ by several orders of magnitude in the IR range. The effect is weak since at distances $d \lesssim 100$ nm, the main contribution to the force comes at the near IR and visible frequencies where the optical difference between the materials is small. On the other hand, the force contrast up to 50% is observed between Au and ITO[33] because the dielectric functions are essentially different up to the UV range.

The PCM materials represent a special class used for rewriteable data storage. These materials were designed for the rapid and reversible switching between the amorphous and crystalline phases since the optical properties of the phases in the visible range are very different.[40] The dielectric function of AIST was measured,[34] and its imaginary part is shown in Fig. 1(c). A significant difference between the phases is observed for frequencies $\omega \lesssim 2$ eV. The increase in absorption for the crystalline state was attributed to the resonance bonding in the visible range[40] and to the charged free carriers in the IR range.[41]

The forces between Au and different phases of AIST were measured in the experiment[34] as shown schematically in Fig. 1(b). The forces for amorphous and crystalline phases are clearly different as one can see in Fig. 1(c) (inset). The PCM is a promising candidate for achieving significant force contrast without composition changes. Moreover, no power has to be applied to keep the state that is a strong advantage for switches.

However, *in situ* switching in response to simple stimuli (e.g., laser heating) at high repetition rates has not been demonstrated yet. To achieve this goal, one has to heat a thin PCM film with a focused laser beam. A fast high energy pulse transforms the crystalline cell into an amorphous state by melt-quenching. The crystalline state can be re-obtained via a longer lower energy pulse. The switching time can be shorter than 100 ns. *In situ* switching of PCMs needs a protective layer because of the required melt-quenching step. A layer of ZnO–SiO_2 is widely used in the recording industry, but this layer will reduce the force contrast.[41] Therefore, additional investigation is needed to choose the composition of the protective layer and minimize its thickness. It should also be noted that as PCMs undergo an amorphous-to-crystalline phase transition, its volume is compressed on 5% − 8%. It will result in the reduction of the film thickness, which can be a challenge for practical realization of *in situ* actuation.

At small separations, e.g., $\lesssim$100 nm, when the Casimir effect dominates over the electrostatics, the stability of a switch becomes an important point. This is because the CF can draw MEMS components together and even lock them permanently into stiction. In fact, this type of permanent adhesion is a common cause of malfunction in MEMS devices. The effect is known as the pull-in instability, in which the CF introduces a new dimension.[42,43] The actuating elements of MEMS are often modeled as a mass-spring system [see Fig. 1(b)], for which the dynamics is described by the following equation:[13,43,44]

$$m\ddot{z} = \kappa(L_0 - z) - F_C(z) - \epsilon(m\omega_0/Q)\dot{z} + \epsilon F_0\cos\omega t, \quad (2)$$

where z is the distance between bodies, m is an effective mass, κ is the spring constant, $F_C(z)$ is the CF, L_0 is the position when the spring is not stretched, $(m\omega_0/Q)\dot{z}$ is the intrinsic energy dissipation (Q is the quality factor), and the last term is a typical external driven force of magnitude F_0 and oscillation frequency ω. Parameter $\epsilon = 0$ corresponds to autonomous conservative motion, while for $\epsilon = 1$, the system performs non-conservative motion, which is the general case in real systems. Studies so far have shown that the geometry and/or the material optical properties that give higher CF will result in higher possibility for unstable behavior toward stiction. For non-conservative motion, increased chaotic behavior limits reliable prediction of the long-term actuation behavior of a dynamical system favoring increased possibility toward stiction.[13,14,44,45] Chaotic behavior occurs if the separatrix (homoclinic orbit, external white curve in Fig. 2) of the conservative system splits.[13,14,44,45] In fact, as Fig. 2 shows, the available phase space for stable motion decreases drastically upon increasing material conductivity from SiC to AIST(A → C) to Au due to increasing CF and, as a result, higher possibility to stiction. Therefore, the optical properties of materials are highly necessary to be measured and incorporated into the design for devices operating at short separations (<200 nm) where the CF is strong enough to lead to chaotic motion and subsequently stiction.

The important role of the CF in adhesion is not always recognized since it is usually attributed to vdW forces. Due to natural roughness, the adhered surfaces are separated by an average distance d_0. The area of the real contact, where the strong vdW attraction operates, is rather limited. However, the much weaker Casimir attraction operates at distance d_0 across the entire nominal area of adhesion. Therefore, the actual force dominating the adhesion is defined by the roughness and by the distance d_0. This fact was demonstrated experimentally using adhered cantilevers with engineered roughness.[18]

Indeed, the average distance d_0 and area of the real contact are crucial parameters for adhesion, friction, heat transfer, lubrication, sealing, and electric conductivity. A method allowing the calculation of the area of the real contact was proposed[46] for self-affine roughness

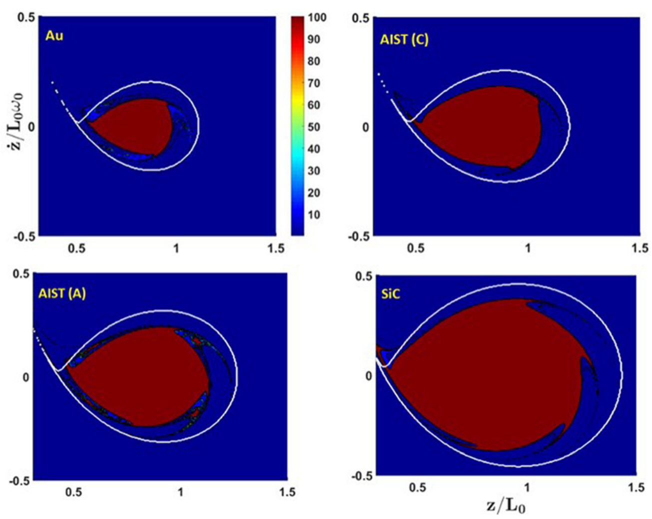

FIG. 2. Poincare portrait velocity vs position of the transient times to stiction for $\epsilon = 1$, a grid of 350×350 initial conditions, $L_0 = 150$ nm, $\omega_0 = (\kappa/m)^{1/2} = 300$ kHz, $Q = 10^4$, and $\omega/\omega_0 = 0.9$. The color bar shows the time elapsed until stiction occurs after 100 oscillations for the interacting materials.

with normal height distribution. The model assumes only elastic deformation of the asperities. However, in many practical situations, significant plastic deformation occurs. Suppose that the nominal pressure P_{nom} on a circle with diameter L is applied to the only high peak, then, based on the Hertzian contact, the local pressure P_{loc} to this peak is estimated as

$$P_{loc} = P_{nom}^{1/3}\left(8E_{eff}Lh/3\pi\xi^2\right)^{2/3}, \tag{3}$$

where E_{eff} is the effective Young modulus of the materials, h is the height of the peak, and ξ is the diameter of the peak at the bottom (the ellipsoidal shape is assumed[47]). Even for a relatively soft contact between a sphere and plate in the condition of the CF experiment[48] ($P_{nom} = 800\,\text{Pa}$, $E_{eff} = 50\,\text{GPa}$ for Au–Au, $L \approx 4\,\mu\text{m}$, $h = 10\,\text{nm}$, and the correlation length $\xi = 25\,\text{nm}$), one finds $P_{loc} = 156\,\text{GPa}$. This value considerably exceeds the plastic yield for gold that is in the range of $P_{pl} = 200 - 250\,\text{MPa}$. Hence, at the contact, many high peaks will be deformed plastically until the pressure in the real contact area becomes equal to P_{pl}. This problem has not been addressed yet and demands both theoretical and experimental attention since the high asperities play the most important role during contact.

Analysis of the AFM images of gold films with different roughness demonstrated that the distribution of the high peaks is described by the extreme value statistics rather than the normal distribution.[48] In Fig. 3(a) (inset), one can see that $\ln\ln(1 - \mathcal{P}(z))$ behaves linearly

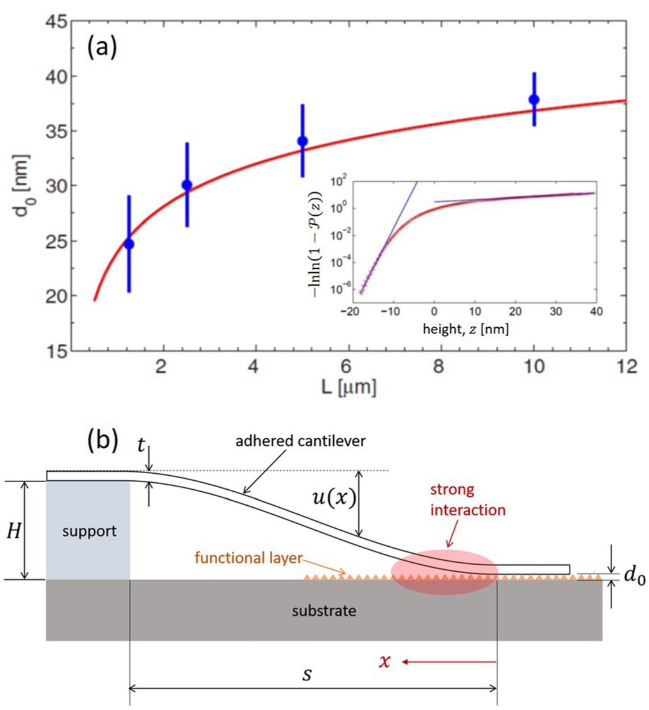

FIG. 3. (a) The height of the highest peak as a function of the area size L. Blue dots are the values found from the AFM scan of the 400 nm thick Au film; the red curve is the theoretical prediction (see details in Ref. 48). The inset shows the cumulative distribution of the peak heights $\mathcal{P}(z)$. (b) Schematic of the adhered cantilever experiment. The strong dispersion forces acting in the highlighted area influence the shape of the cantilever $u(x)$.

with the height z for high peaks or deep pits. This distribution yields a theoretical prediction for the height of the highest peak in the area L^2. The same values can be found from a detailed AFM scan.[48] Figure 3(a) shows the highest peak on the area with the size L.

The ability to predict d_0 allowed us to explain[47] the deviation from the expected scaling in the measured CF at relatively short distances.[49] The deviation from the normal Casimir scaling $F_C(z) \propto z^{-\alpha}$ (α is nearly a constant) occurs because of the contribution from the high peaks, which approaches very close to the opposite surface. The model proposed in Ref. 47 treats these peaks additively because the average distance between rare high peaks is large in comparison with their lateral size ξ. In this way, we can address a quite complicated problem: how one can calculate the force, if the distance between the surfaces becomes comparable to the roughness amplitude. The adhesion is a special case of this situation. However, the method has an important restriction. For the determination of d_0, the zero load limit was assumed so that the high peaks are not deformed at all. This can be justified when no contact is present between the surfaces, but it is definitely not the case for adhesion. Therefore, an important point for future research is theoretical and experimental determination of plastic deformations of the high peaks in conditions of the adhesive load. It will open a possibility to predict d_0 at the contact and determine the area of the real contact. As a result, we will be able to predict the adhesion forces induced by the dispersion interaction using as input the roughness statistics and mechanical and optical properties of the materials.

This program has been proposed recently.[19] An adhered cantilever [see Fig. 3(b)] is a promising system to investigate the adhesion and roughness effects in the CF. The measurement of the forces at distances $z \sim 10\,\text{nm}$ is problematic because the systems with elastic suspension lose stability at small distances and jump to contact. The adhered cantilever does not suffer from this problem. It was demonstrated[50] that strong dispersion forces acting near the adhered end (see the highlighted region) contribute to the shape of the cantilever and this contribution is measurable. On the other hand, the measurement of the unadhered length s is related to the adhesion energy per unit area.[51] Therefore, such a system can be used for investigation of the forces at short separations including the region of adhesion. In the latter case, we should be able to distinguish between the short distance vdW contribution (at the contact) and the Casimir contribution across the average gap d_0.

In conclusion, we considered three main directions as prospective applications of the CF. The possibility to generate a repulsive force is promising for many applications, but it is difficult to realize because of material restrictions. We did not discuss this possibility in detail. The application of the CF for actuation of MEMS/NEMS is very natural since it can dominate the electrostatic actuation at distances below 100 nm. Actuation with the PCM was considered in detail. The third direction is the adhesion induced by both vdW and Casimir forces. This effect is already used in natural and artificial systems, but some critical points that demand better understanding were stressed.

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DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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