C. R. Physique 12 (2011) 898–907

Contents lists available at SciVerse ScienceDirect

Comptes Rendus Physique

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Presence of electromagnetic fluctuations in micromechanics

Influence des fluctuations électromagnétiques en micromécanique

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ARTICLE INFO

Article history:
Available online 16 November 2011

Keywords:
Quantum fluctuations
Casimir force
Microsystems
Atomic Force Microscopy
Near Field Heat Transfer

ABSTRACT

Micro electromechanical systems (MEMS) and mechanical effects of quantum fluctuations become strongly related. MEMS have allowed the production of important experimental results such as quantitative measurements of the Casimir force at the micro- and nanoscales. MEMS are used to probe these effects because they are sensitive to them and engineers will certainly have to increasingly consider the effects of quantum and thermal fluctuations in the design of MEMS that are used as actuators and sensors. These effects on MEMS are controlled by the electron–photon coupling. These questions are then coupled to new fields of research, such as photonics and plasmonics.

RÉSUMÉ

Les microsystèmes électromécaniques (MEMS) et les effets mécaniques dus aux fluctuations quantiques sont fortement reliés. Les MEMS ont permis la mesure quantitative de la force de Casimir à l'échelle micro et nanométrique. Si les MEMS sont une bonne sonde de ces effets, c'est parce qu'ils y sont très sensibles et cela signifie la nécessité pour les ingénieurs de mieux prendre en compte à l'avenir l'effet des fluctuations quantiques ou thermiques sur les MEMS utilisés comme capteurs ou actionneurs. Ces effets sont dus aux propriétés du couplage électron–photon et ces questions sont ainsi liées à la plasmonique et à la photonique.

1. Introduction

A classical description of the coupling between charges, currents and electromagnetic fields is at the heart of the Maxwell equations. It is well known, however, that a proper description of a solid or molecule cannot be done without a quantum description which involves the zero temperature kinetic energy of electrons, i.e. the quantum fluctuations of electrons. This is the so-called zero-point motion of electrons associated to the quantum confinement. There is similarly a zero-point motion of the electromagnetic field which is nowadays ascribed to the energy of the vacuum. Quantum Electrodynamic (QED) enables one to consistently describe the coupling of photons and electrons. Virtual exchanges of energy between the electrons and the electromagnetic field in vacuum at zero temperature is one spectacular example. This has consequences up to our scale. The gecko lizard became a star in nanotechnologies certainly because its ability to walk on any vertical smooth wall appears to be a consequence of this virtual energy exchange at the atomic scale between its nanostructured

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1631-0705/$ – see front matter
doi:10.1016/j.crhy.2011.10.014

feet and the wall. In the case of the two atom interaction, this coupling is described in details in [1]. This leads to the van der Waals description at very short distances where electron fluctuations dominate and to the Casimir–Polder [2] description at larger distances where the speed of light is no longer considered as infinite and where vacuum fluctuations of the electromagnetic field in vacuum dominate. For extended mirrors, the same distinction remains valid. At very short distances, a few nanometers, the interaction between two mirrors is modeled by the van der Waals description, which is essentially here the coupling of surface plasmons between the two surfaces. At larger distances, the "optical" description proposed by Casimir [3] stands. It is based on perfect mirrors and ignores the electronic properties of the mirror materials. Modern approaches are essentially able to quantitatively describe the resulting mechanical interaction between any mirrors in vacuum [4] at any distances. The Casimir model leads to an estimate of the induced force between two parallel mirrors. At a distance separation of 100 nm, the pressure that is associated to the attractive interaction between two mirrors is close to 10 Pa. In MEMS, the typical area of interacting surfaces is 10 μm × 10 μm, which results in a force close to 1 nN. Such a force is nowadays easily measured by Atomic Force Microscope related techniques. This simple estimate shows that the Casimir force might no longer remain a curiosity in laboratories but becomes a tool for engineers working with MEMS under vacuum.

Probing mechanical and thermal effects of quantum and thermal fluctuations in the electron–photon coupling is indeed an increasingly active research field. The focus is at least on two points: the van der Waals/Casimir interaction and the heat transfer in the near field. Although interactions at the nanoscale are clearly very diverse, these two effects have in common to be present in most real situations. The van der Waals/Casimir interaction cannot be suppressed and the second exists as soon as a temperature gradient exists between interacting surfaces separated by a micrometer gap. References in [4] gather reviews that describe the Casimir force and the context of interactions at nanoscale. A central motivation of these papers lies in the fact that Micro Electromechanical Systems (MEMS) and Atomic Force Microscopy (AFM), key fields in nanotechnologies, are deeply connected to the emergence of a strong interest in both fields. We shall try to show here that MEMS and AFM are simultaneously experimental tools or probes of these effects and the center of technological researches that investigate how these fundamental effects might have an impact on their operation. MEMS are indeed of increasing importance in daily life technologies [5] and their functioning involves ever more sophisticated structures at the micro- or nanoscale, where these effects are ruled by power laws with large negative exponents. These are major reasons for the research programs nowadays undertaken on the role of quantum and thermal fluctuations in MEMS/NEMS operation [6].

Over the years and since the occurrence of quantum mechanics, theoretical research has been continuously active on both aspects, mechanical and thermal effects due to fluctuations in the electron–photon coupling, sometime simultaneously on both aspects. Quantitative experiments have however been expected for about 40 years in both cases. In this paper, we shall use our recent measurements [9] and those of some prominent groups [8–15] to show that the use of nanotechnologies such as highly controlled positioning at the nanoscale is indeed at the root of these recent developments in the experimental investigation of the Casimir force. The fact that nanotechnologies have played a significant role in the rapid but recent emergence of this field is somewhat associated to a characteristic length in the problem, that is the spatial extension in vacuum of evanescent electromagnetic waves, either due to plasmon polariton or phonon polariton at the solid surfaces [16–19]. Surface plasmon polariton is associated to a collective fluctuation of the charge density of electrons at the surface. In polar materials, the surface phonon polariton is a collective distortion of ion distribution at the surface. When two surfaces are brought close enough, the overlap of the associated evanescent waves very much controls the strength of the coupling between interacting surfaces. These evanescent waves extend in vacuum with characteristic lengths close to 100 nm (surface plasmon polariton in metals) and a few micrometers (surface phonon polariton in glass or silicon carbide for example). Symmetrically, MEMS are used more and more in controlled environments including vacuum and are built with gaps between highly parallel and smooth surfaces always smaller and often much smaller than the extension of the evanescent waves of collective surface excitations. This might have a list of practical consequences. The presence of the van der Waals/Casimir force might change the performance and the mechanical stability of devices such as accelerometers that are usually and classically designed taking into account primarily the electrostatic interaction. Playing with the nature of materials and with their shape (thickness of a surface layer for instance) can also change the influence of the Casimir force on the behavior of the MEMS involved. This is shown by numerical simulations of interacting silicon slabs with varied doping levels [20].

In the case of heat transfer, distances between interacting surfaces can be decreased to such an extent that the heat transfer is essentially controlled by the surface excitation which is monochromatic. It has therefore been proposed to use the highly monochromatic heat transfer between the hot source and the cold reservoir to more efficiently transform this heat into electricity using a well adapted electronic transition [21]. This proposal includes the development of near-field thermophotovoltaic (TPV) devices. Research programs have been recently proposed in this area. Again, micro-devices will certainly be at the heart of the technological choices made in the development of an efficient solution.

We therefore emphasize three aspects that link MEMS or AFM to effects of quantum or thermal fluctuations. They are the guidelines of this paper.

First, MEMS and AFM are not the only way to probe different aspects of these effects [22,23] but they have allowed the production of some of the most important experimental results in the field and their use has certainly triggered advanced research programs [6].

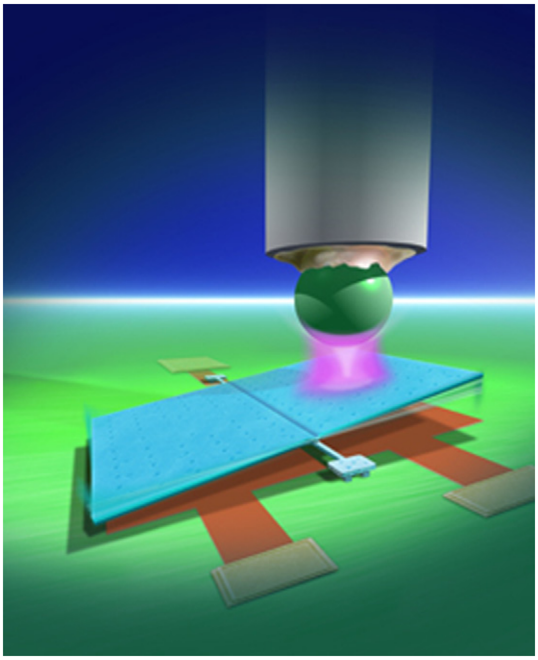


Fig. 1. This image is a symbol as it depicts the interplay of the Casimir force represented as a pink field and of the MEMS structure that is the bottom part of the image. It has been taken from the website of F. Capasso group at Harvard University [7]. Image source Bell Labs. It summarizes most of the concepts here developed. The vertical cylinder is a piezoelectric element that controls the microsphere position. The blue oscillating micro-plate is the upper part of the MEMS that is electromechanically actuated. The overall size of the system is less than 500 μm. The MEMS is then sensitive enough to be able to detect the Casimir force and its spatial variation as the sphere–plane distance is varied [8]. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

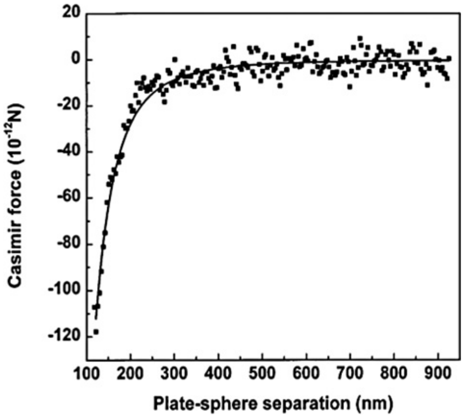


Fig. 2. This figure is the original one published in the paper entitled: "Precision Measurement of the Casimir force from 0.1 to 0.9 μm" by U. Mohideen and A. Roy [10]. It presents the measured variation of the Casimir force as the distance between a gold plated microsphere and a gold film is changed.

Second, MEMS are used to probe these effects because they are affected by them. This means that engineers will certainly have to consider more and more these effects when they design MEMS. Fundamental results here described are also informations given to make progresses in these directions.

Third, as illustrated below by the importance of characteristic lengths associated with surface collective excitations, these effects, which are important in the non-contact interaction of surfaces, are also related to new, important and growing fields such as photonics and plasmonics.

The first point is revealed by the repeated tentatives to use metamaterials to control the Casimir force [24]. The second is found in the clear parallel established between the optical forces associated to light irradiation and the Casimir effect [25]. One way to control the Casimir force that is currently investigated is based on the tuning of plasmon–photon coupling using surface nano-structuration [13,26].

2. Interacting surfaces through electromagnetic fluctuations

The importance of electromagnetic fluctuations for mechanical interactions or energy exchange between two objects has been identified soon after Quantum Mechanics has been built [2,3,27–30]. Nowadays their measurements and detailed investigations clearly benefit from the ability to produce MEMS and to use detection scheme that have been developed in the context of Atomic Force Microscopy (AFM). Within this context, the experiment performed by the group of U. Mohideen [10] appears as a landmark.

After historical measurements done by B.V. Derjaguin et al. [30] and M. Spaarnay [31] in 1958 (this last paper reports an error bar around 100% and contains this famous often quoted sentence: the measurement "did not contradict Casimir's theoretical prediction"), it is certainly the first truly quantitative measurement of the Casimir force. Compared to previous attempts such as the one produced by S. Lamoreaux [22], this result is based on two major experimental points: i) it uses a microsphere/plane geometry which, for a long time (it essentially still remains), makes the Derjaguin or Proximity Force Approximation (PFA) a central aspect of this field as it is necessary to compare experimental results and theory mostly based on the plane–plane interaction; ii) in contrast with previously developed and dedicated Casimir experimental set

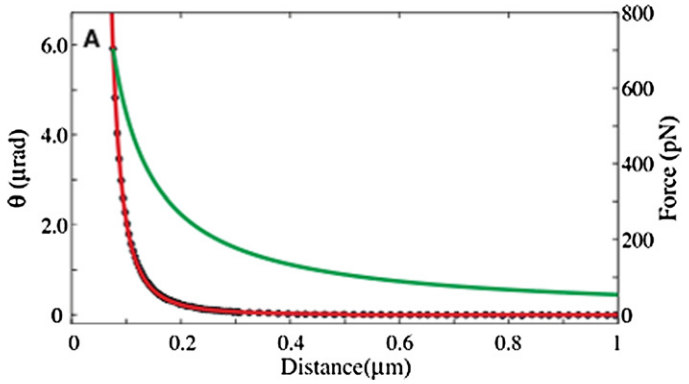


Fig. 3. From Ref. [8], measurements performed using the system illustrated in Fig. 1, demonstrating why Casimir force and MEMS must have such a strong connection. The green curve shows the electrostatic force as the voltage between the sphere and the plate is fixed at 0.136 V, a typical voltage used to actuate MEMS. The black points are the measured data of the Casimir force. The red curve is a theoretical analysis. This shows that at short distances, the Casimir force can equal a typically used electrostatic force.

up, U. Mohideen group based his experimental set up on well-established force measurement techniques coming from the Atomic Force Microscopy (AFM) [32]. This is shown in Fig. 2. The major instrumental change is the use of a calibrated and very smooth gold plated microsphere instead of the regular but usually not well characterized AFM nanotip.

The group of F. Capasso opens a new path soon after by using a MEMS to investigate and to measure the Casimir force. He simultaneously showed that the Casimir force can influence the functioning of MEMS as surfaces in MEMS are closer and closer and interact under vacuum in a cleaner and cleaner environment. This is shown in Fig. 3. In 2001, this group then made the connection between MEMS and quantum fluctuations explicit. The title of their article [8] is worth mentioning here: “Quantum Mechanical Actuation of Microelectromechanical Systems by the Casimir Force”.

This first MEMS used to probe the Casimir force has been developed at Bell’s Labs. The ones used today to better probe the Casimir force are still very close to this one [12]. Most of the groups that have tried to produce quantitative measurements of the Casimir force have followed this track based on AFM force detection and positioning techniques, and on the sensitivity of MEMS to very small forces [8–15]. Among the most advanced measurements in term of precision and control produced so far are those of R.S. Decca [11,33] and H.B. Chan [13]. In both cases, these are based on the use of MEMS.

3. Characteristic lengths and micro/nanotechnologies

Historical references immediately highlight a characteristic point in this field: the time delay between some of the major theoretical contributions and the production of precise measurements. Milestones in theory certainly are in 1948, H.B.G. Casimir [3], in 1955, E.M. Lifshitz [34] and later I.E. Dzyaloshinskii, E.M. Lifshitz, L.P. Pitaevskii [35]. This is also the time when the fluctuation–dissipation theorem has been put on a firm basis [36], which is an important tool in this field once effects of thermal fluctuations are considered. The specificity of heat exchange between two surfaces at very short distances based on the coupling of thermal surface electronic excitations has been addressed during the same period. See, for example, the books of S.M. Rytov [37]. This is both theoretically and experimentally a problem very close to the Casimir field. The fact that the blackbody radiation would not be the relevant framework to describe the heat exchange between two surfaces at very short distances seemed to have been mentioned by Planck as soon as he established the blackbody theory [38]. Again, concerning radiative heat transfer in the near field [36], although key aspects of the theory have been produced 40 years ago, this is only the use of techniques coming from Atomic Force Microscopy and MEMS that have given us today the ability to quantitatively probe these effects [39,40].

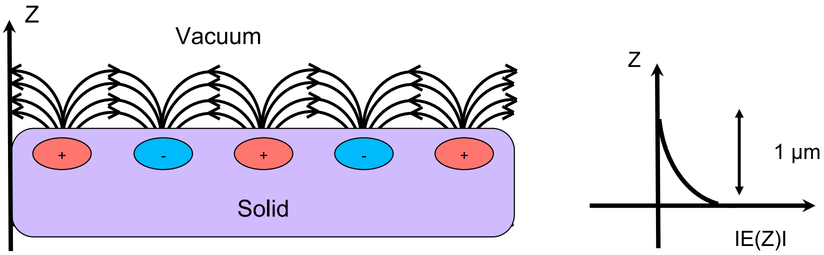
Following this analysis, it will be interesting to observe in the near future if the recurrent experimental question of probing mechanical effects between two interacting surfaces in plane–plane geometry can be efficiently approached following the same strategy, that is using nanotechnologies to develop the necessary experimental set up [41,42].

The experimental study of the interactions between objects due to electromagnetic fluctuations clearly belongs to the recently born field of nanomechanics. The fact that relevant distances for this problem are in the micro- or nanometer scales is shown by the length associated to charge fluctuation energy at the surface.

The surface collective excitation that determines this length is either a plasmon polariton for van der Waals/Casimir force, or a phonon polariton for the heat transfer [18]:

$$\lambda_\mathrm{p} = 2\pi c/\omega_\mathrm{p}$$

At separations much shorter than λ_p, the force due to quantum fluctuations is adequately described using the van der Waals model where most of the fluctuations are due to collective excitations of electrons at the surface. As the separation increases and becomes much larger than λ_p, the force is expected to be better described by its asymptotic limit, which is nothing but



(a) (b)

Fig. 4. Electric scheme inspired by [38]: a) evanescent electric field distribution close to a planar surface; positive and negative electric charges are illustrated by the green and red regions, respectively; b) exponential decrease in field strength as the distance from the surface (z) is increased, with a typical 1-µm spatial extension in vacuum for the evanescent wave associated to thermally-excited surface phonon polaritons. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

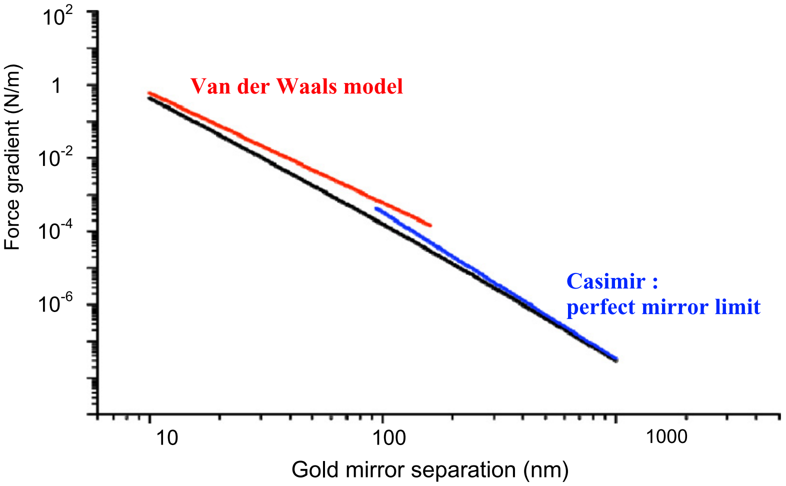


Fig. 5. Force gradient between a 40 µm gold plated sphere and a gold plane. The two limiting regimes are shown. The van der Waals model predicts a gradient varying as L^{-3}, the Casimir regime as L^{-4}.

the Casimir model. In this regime, the interacting surfaces become perfect mirrors. Fluctuations are essentially described as quantum fluctuations of the electromagnetic field in vacuum. All this is shown in Fig. 5.

For metals, the length λ_p associated to the surface plasmon energy is close to 100 nm (Handbook of optical properties indicates 138 nm for gold). It is much larger and closer to a micrometer in the case of a phonon–polariton at the surface of dielectrics such as SiC or glass. This is shown in Fig. 4. This length difference is classically due to the mass ratio between an electron and an ion.

These characteristic distances must be combined with the value of the force between two perfect mirrors at this distance. Following Casimir formula [3], the attractive force can be estimated using:

$$F_{\mathrm{Cas}} = \frac{\hbar c \pi^2 A}{240 L^4}$$

For a distance $L = 100$ nm and a surface A of interaction of 10 µm × 10 µm, as previously written in the introduction, this equation gives a force estimate close to 1 nN which can be compared to a typical “chemical force” measured in Atomic Force Microscopy (1 eV/nm, close to 1 nN), or to the forces associated to the thermal energy at the nanoscale ($k_B T/a$ which is close to a few piconewton for $a = 1$ nm), or also to entropic forces in molecular unfolding [43].

Heat transfer at short scale had to wait even a longer time for a first experimental evidence. It has been provided by research programs on thermal transfer triggered by the Apollo program [44]. Several important references such as [45] around 1970 have clearly reported an anomaly in the heat transfer at very short scale under the vacuum. Following the work of S.M. Rytov [37], D. Polder and M. van Hove [19] gave a thorough theoretical analysis which contains key elements to understand this increase of the thermal transfer at short scale due to the overlapping of electromagnetic evanescent waves associated with thermal charge fluctuations. No precise measurement of the heat transfer versus the separation distance could however be produced at this time. It was only in 2009 that two groups simultaneously published results reporting a quantitative analysis of the large increase of the thermal transfer at short scale [39,40]. This is shown in Fig. 6. It then appears that if major theoretical contributions have been produced in the description of interaction between surfaces due to electromagnetic fluctuations from 1948 until now, precise measurements have been expected for about half a century.

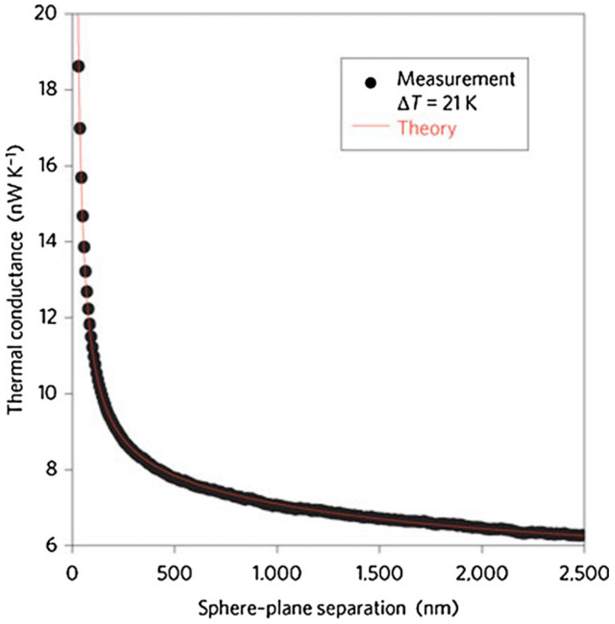


Fig. 6. This figure is from [39]. It shows the measured thermal conductance between a microsphere and a plate as the separation is varied from about 100 nm up to 2.5 μm. The black dots represent experimental data and the red line the theoretical model. The temperature difference between the plate and the sphere is 21 K. The sharp increase as the distance is reduced is due to the near field thermal transfer contribution which is triggered when the separation becomes comparable to the phonon polariton evanescent wave extension. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

In this article it is argued that MEMS and AFM techniques provide great experimental tools to enter Casimir force measurements. However, although they match the relevant characteristic lengths with their geometrical structures, and have proven that they are highly successful, it is of course first not an absolute necessity to use them and second not a universal relevant tool to probe these effects. Casimir force measurements have been put back on the scene in 1997 by S. Lamoreaux [22] using a macroscopic torsional pendulum experiment and by G. Bressi et al. [23]. In this last experiment, the Casimir force has been measured between two large plane and parallel mirrors for separation varied between 0.5 μm and 3 μm at the 15% precision level. One also observes that surfaces prepared using techniques developed for MEMS are not necessarily the relevant ones for the study of the increased heat exchange in near field coupling. Within the LIGO Program, R.S. Ottens and D.B. Tanner have built an experiment that uses the near field thermal transfer between two parallel and plane sapphire surfaces. They want to demonstrate that it could be an efficient noncontact channel to cool LIGO mirrors [46]. Their set up is designed so that they are probing how the heat could be extracted from the large mirrors used in LIGO. It is then optimized to operate at a large separation, that is a few micrometers with large interacting surfaces (square centimeter). For these values of the gap and taking into account the large surfaces, they do not make use of the MEMS techniques.

Investigation of the thermal Casimir effect due to thermally activated fluctuations also clearly shows that MEMS are not always the right basis to define an experimental set up. A few orders of magnitude will show that MEMS are not relevant to study this problem which probably has no influence on the behavior of realistic MEMS. Another characteristic length is the one at which thermal fluctuations start to dominate the force behavior. This distance can be represented by:

$$\lambda_{\mathrm{th}} = ch/k_{\mathrm{B}}T$$

Producing a measurement that precisely reveals the behavior of the Casimir thermal effect at distances in the vicinity of λ_{th} is under way in some groups. This is experimentally a very difficult challenge as it is then necessary to measure the Casimir pressure at separation larger than micrometers and to insure that any additional unrelated contribution can be identified and safely removed.

A likely drawback in the use of AFM and MEMS techniques is that their use is confined to measurements at short separation distances. A rough estimate using Casimir formula for interacting surfaces with size of 10 μm shows that the interacting force is reduced to 1 aN for a separation close to 5 μm. This is approximately the distance where the thermal fluctuations should have an important influence on the Casimir force in conventional situations. A force of 1 aN has been measured using AFM like techniques but in a very different context. It seems very difficult to use MEMS and AFM techniques to measure the thermal contribution to the Casimir force at large gap values between interacting surfaces.

This thermal Casimir effect is then the regime where the use of MEMS and AFM, techniques coming from nanotechnologies might be of limited interest. Conversely, as this thermal Casimir effect becomes relevant at large distances for reasonable temperature values, it will certainly remain of limited interest, if any, for nanotechnologies. Discussion of the

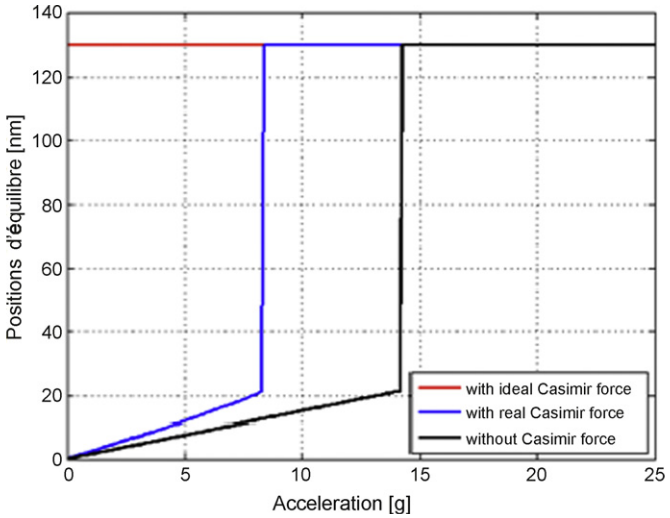


Fig. 7. From Ref. [48]. The black curve describes the position of a mobile micrometer mass linked to nanosprings and whose displacement induced by acceleration is detected by a classical capacitive system. If the displacement becomes too high, the mass is irreversibly attracted by the neighboring surfaces. This effect is the so-called "pull in" effect. It is most often due to electrostatic interaction. Here it is shown that the Casimir force can severely reduce the acceleration value where this happens (the blue curve shifted to smaller accelerations). Although it is a numerical analysis, it clearly illustrates how large can be the influence of the Casimir force on MEMS structures, especially if they present large surfaces of interaction and narrow gaps as chosen here (gaps are close to 100 nm and characteristic area of interacting surfaces is around 2.5 µm × 2.5 µm). The red curve shows the effect of the Casimir force estimated using the original and ideal Casimir model which at these distances overestimates the force and the induced effect.

measurement of the thermal effect is therefore out of the scope of this paper although recent and important results have been published on the thermal Casimir effect [47].

4. Influence of Casimir effect on MEMS behavior, materials choice and shape definition

In this section, we address three major questions dealing with the influence of the Casimir interaction on the operation of MEMS:

(i) How can the Casimir force influence the behavior of a MEMS. This can be seen first through an alteration of the so-called "pull in" effect which is the inherent mechanical instability of these structures due to a strong gradient of attractive forces that can overcome the system mechanical stiffness. This effect of the Casimir force on MEMS/NEMS is described in detail in [48]. A central effect is shown in Fig. 7.

(ii) Optical properties of the interacting surfaces are key parameters for the determination of the Casimir effect. These optical properties are essentially determined by dielectric constants and by the material shape. During the last ten years, it has been a challenge to show that the Casimir force can be properly measured not only between gold interfaces under vacuum and that variations of the Casimir force due to controlled changes of the optical properties can be clearly measured. This is what has been achieved by the group of D. Iannuzzi [49] and is here shown in Fig. 8. The interaction between a gold plated sphere and a gold surface is compared with that between a gold sphere and an ITO surface. ITO stands for indium tin oxide which is a conductive oxide. Authors show that they measured the Casimir force in both cases and that the force is significantly reduced in the second case as expected from theory. An important aspect is the fact that this result has been measured in air. The emphasis is here put first, on the original real time measurement scenario for data acquisition and calibration and second, on the temperature stability of the whole set up. Other clear-cut very similar examples have been produced by G. Torricelli et al. [50].

Another major situation where the change of optical properties is expected to induce changes in the Casimir force, is described in [20]: the Casimir interaction between silicon surfaces can be profoundly changed by varying the doping level (see Fig. 9).

To my knowledge, clear experimental evidence has not been conclusively produced for this detailed influence of the doping level although numerical demonstrations show strong effect at distances close to 1 µm [20]. Beside this "chemical effect" on the force behavior as the doping level is varied in silicon, numerical calculations show that the force can also be influenced by the mirror thickness. A very crude explanation, i.e. a thumb rule, is that virtual photons that dominate the Casimir force at a given distance are the ones with wavelength close to the cavity size determined by the two mirrors. At distances larger than 1 µm, in the infrared regime, intrinsic silicon becomes gradually transparent for the associated photons and this corresponds to a large relative decrease of the Casimir force.

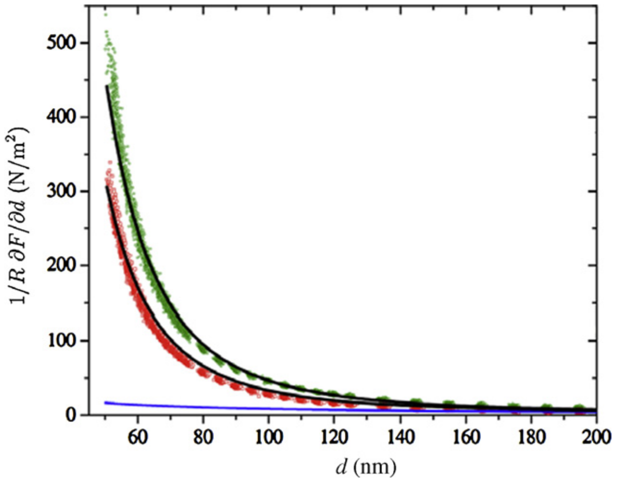


Fig. 8. Casimir force gradient as a function of absolute surface separation for Au–Au (green squares) and Au-ITO (red squares) surfaces. The blue line represents the derivative of the electrostatic force caused by the simultaneous calibration procedure (common to both the gold and ITO measurements).

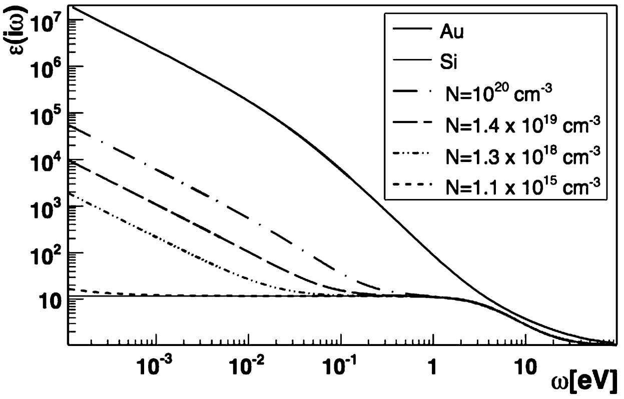


Fig. 9. From Ref. [20]. The different dielectric functions for intrinsic and doped silicon for varying carrier densities, in comparison with gold. Such a change is expected to have a significant effect on the Casimir force intensity.

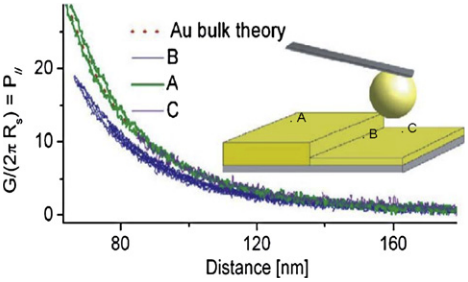


Fig. 10. From Ref. [9]. Two gold mirrors are shaped in the well-defined sphere–plane geometry. The microsphere is the probe and the plane is a flat structured film: left part is 300 nm thick, right part, is 10 nm thick. Measuring the Casimir force on the thinner film showed the expected skin effect but also revealed large spatial variations of the force. Somewhat as a paradox, local measurement of the Casimir force here appears as a sensitive tool to investigate changes in film properties that are not easily measured by others techniques. Curve A is measured on the thick part (left side), curves B and C at two different locations of the shallow part (right side). The Casimir force is reduced as expected only at B and not at C.

Measurements on silicon slabs of different thicknesses or different doping levels have not been produced yet. The fact that a mirror becomes somewhat transparent for extremely small, nanometric, thicknesses is however by no means limited to semiconductors. A similar thin film effect has been described and measured by at least two groups on metallic thin films [51,9]. See Fig. 10.

(iii) The Casimir effect is very much related to the frontiers of vacuum. It has been theoretically shown that quantum fluctuations are strongly affected by the shape of interacting surfaces [52]. This is now experimentally investigated and might

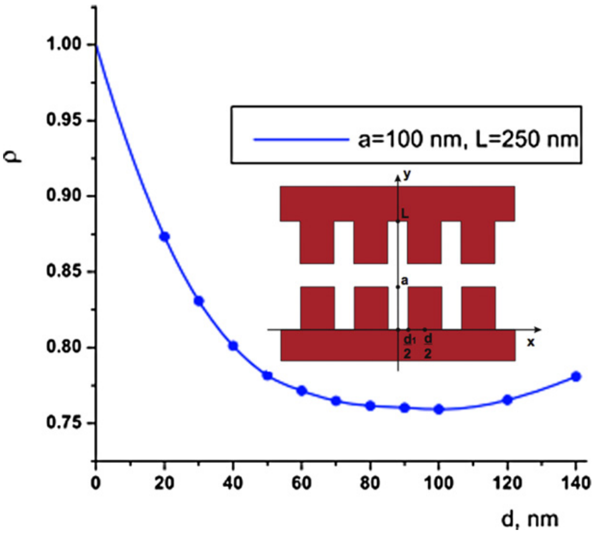


Fig. 11. From Ref. [26]. ρ is the Casimir force normalized by the calculated PFA value for two Si gratings. Height of the grating is $a = 100$ nm. L is the reference distance between the two surfaces. It is measured at the bottom of the groove. The ratio ρ is plotted as a function of d at a fixed distance $L = 250$ nm.

become of interest to control the influence of the electron–photon coupling in MEMS. Experimental investigations probing changes of the force due to the surface nanostructuration are coming from at least two groups [53,13]. Theoretical approaches such as [54] now produce quantitative numerical calculations that go beyond the local approximation often used to treat in a simple way complex geometry using the plane–plane geometry as a reference (this is the so-called Proximity Force Approximation or PFA which is commonly used although the Casimir force is clearly based on nonlocal effects). In Ref. [26], effects of gratings at the surface are thoroughly analyzed to demonstrate a nontrivial result as a non-monotonic variation of the force compared to the PFA description is found when the surface parameters are varied. This is shown in Fig. 11 from Ref. [26].

This result contributes to connect the control of quantum fluctuations in their actions on mechanical effects to the field of photonics and plasmonics whose one central goal lies in the tailoring of electron–photon coupling in micro- and nanostructures. It also shows that several theoretical groups [26,55] are ready to calculate the effect of the Casimir force in the complex structures of modern MEMS. This might become important in a near future as the more controlled and the more compact are the MEMS, the more relevant is the Casimir force in their operation.

However, somewhat surprisingly, experimentalists who investigate the Casimir force are still seemingly dragging behind both theoreticians and engineers who produce vacuum gaps at the nanoscale. One reason might be that they have now to enter the precise measurement of the Casimir force using plane–plane geometry. This means that, beside the control of the varied separation distance with a very high precision, the measurement of the force and the annihilation or the compensation of all spurious forces, they will have to add the control of two angles θ and φ, to produce parallelism with a needed precision certainly close to what is achieved on X-ray diffractometer to measure the Bragg diffraction of a perfect silicon crystal [42].

Acknowledgements

This article is the result of numerous discussions and collaborations with many colleagues. Among them: P. Andreucci, F. Comin, L. Durrafourg, J.J. Greffet, S. Huant, D. Iannuzzi, G. Jourdan, A. Lambrecht, J. Laurent, S. Reynaud, A. Siria, H. Sellier, G. Torricelli. It is a pleasure to acknowledge how these discussions have been important for me. Many informal analysis have taken place within the European Science Fundation Network (2008–2013) New Trends and Applications of the Casimir Effects (CASIMIR).

The associated experimental researches at Grenoble have been performed in consortium based on the Institut Néel (CNRS/UJF), Laboratoire Kastler Brossel (ENS/UPMC/CNRS), Laboratoire Charles Fabry (Institut d'Optique/CNRS/UPS), ESRF and LETI-MINATEC (CEA Grenoble). It has been essentially funded by the ANR project Monaco (ANR-06-NANO-062), the Institut Carnot LETI and the European FP6 project X-Tip (STRP 505634-1 X-TIP).

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