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View online: https://doi.org/10.1016/j.jnlest.2020.100024

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Casimir Effect in Optoelectronic Devices Using Ferrofluids

Elena N. Velichko | Galina L. Klimchitskaya* | Elina N. Nepomnyashchaya

Abstract—Some of the modern electronic and optoelectronic devices exploit ferrofluids contained in narrow gaps between two material plates. When the width of the gap becomes below a micrometer, the boundary plates are subjected to the Casimir force arising from the zero-point and thermal fluctuations of the electromagnetic field. These forces should be taken into account in microdevices with the dimensions decreased to below a micrometer. In this paper, we review recently performed calculations of the attractive Casimir pressure in three-layer systems containing a ferrofluid. We also find the ferrofluidic system where the Casimir pressure is repulsive. This result is obtained in the framework of the fundamental Lifshitz theory of van der Waals and Casimir forces. The conclusion is made that enhanced repulsion due to the presence of a ferrofluid may prevent from sticking of closely spaced elements of a microdevice.

Index Terms—Casimir pressure, ferrofluids, microdevices, repulsion.

1. Introduction

Considerable recent attention has been paid to the electronic and optoelectronic devices, such as switches, optical modulators, and biosensors, which exploit ferrofluids for their functionality[1]-[7]. Ferrofluids are colloidal liquids which consist of nonmagnetic carrier liquids (for example kerosene or water) and magnetic nanoparticles (made, for example, of magnetite) suspended in it[8]. To prevent their agglomerations, magnetic nanoparticles are usually coated with a surfactant which decreases the surface tension[8],[9].

Several already devised ferrofluid-based electronic devices are of microscopic character[9],[10]. They may contain a ferrofluid film with the thickness less than a micrometer confined between two material plates. In such cases, these plates are under the influence of an additional force caused by the zero-point and thermal fluctuations of the electromagnetic field[10]. This force is called the Casimir force, and it should be taken into account in microelectronic and nanoelectronic devices with further decreased dimensions.

The first investigation of the role of the Casimir force in three-layer systems consisting of the kerosene- or water-based ferrofluid confined between two SiO$_2$ plates was performed very recently[10][11]. Next, the impact of the
agglomeration of magnetite nanoparticles on the Casimir pressure in the systems of this kind has been examined\[17.\] In [18], the Casimir pressure between SiO\(_2\) and Au plates separated by a kerosene-based ferrofluid was studied. The Casimir pressure was investigated as functions of the thickness of the ferrofluid layer, of the volume fraction of magnetic nanoparticles, and of their diameters. It was shown that magnetic nanoparticles make an important impact on the magnitude of the Casimir pressure in three-layer systems. However, for both kerosene- and water-based ferrofluids confined between SiO\(_2\) plates and also for a kerosene-based ferrofluid confined between one SiO\(_2\) plate and one Au plate, the Casimir force remains attractive.

In this paper, we briefly review the previously obtained results and then continue the investigation of the Casimir pressure in ferrofluid-based electronic and optoelectronic microdevices. As that in [18], we consider the Casimir pressure through a ferrofluid confined between two dissimilar plates, one dielectric (SiO\(_2\)) and another metallic (Au). However, unlike [18], we do not calculate the Casimir pressure through a kerosene-based ferrofluid but through a water-based ferrofluid. It has been known that if the static dielectric permittivity of an intermediate layer in a three-layer system is sandwiched between the dielectric permittivities of outer layers, the Casimir pressure may change its sign from attractive to repulsive with the increasing thickness of the intermediate layer\[19,20.\] This effect was demonstrated experimentally\[19.\] It takes place for SiO\(_2\) and Au plates separated by a water layer. According to our results, the presence of magnetite nanoparticles in water makes the Casimir pressure repulsive over the wider range of the layer thickness. Possible applications of this result to microelectronic devices using ferrofluids are discussed.

2. Lifshitz Formula for the Casimir Pressure through a Ferrofluid

We consider a three-layer system consisting of the metallic plate, the layer of a magnetic fluid (ferrofluid) with the thickness of \(a\), and the dielectric plate. The dielectric permittivities and magnetic permeabilities of these layers are denoted as \(\epsilon^{(1)}(\omega)\), \(\epsilon^{(2)}(\omega)\), and \(\epsilon^{(3)}(\omega)\) and \(\mu^{(1)}(\omega)\), \(\mu^{(2)}(\omega)\), and \(\mu^{(3)}(\omega)\), respectively. It is assumed that both metal and dielectric are nonmagnetic, so that \(\mu^{(1)}(\omega)=\mu^{(2)}(\omega)=1\). With respect to the calculation of the Casimir pressure, the plates are suggested to be infinitely thick. This suggestion is justified if the plate thickness is larger than 100 nm for metals\[14\] and larger than 2 \(\mu\)m for dielectrics\[20\]. Then the Lifshitz formula for the Casimir pressure between the plates separated by the ferrofluid is given by\[14\]

\[
P(a) = -\frac{k_B T}{\pi} \sum_{l=0}^{\infty} \left( \int_0^\infty k dk \right) \rho^{(l)}(i\xi_l, k) \sum_{\alpha} \left[ \frac{e^{2ap^{(l)}(i\xi_l, k)}}{r^{(l)}_\alpha(i\xi_l, k)\rho^{(l)}(i\xi_l, k)} - 1 \right]^{-1}.
\]

Here, \(k_B\) is the Boltzmann constant, \(T\) is the temperature, \(k\) is the magnitude of the wave vector projection on the plane of plates, \(\xi_l = 2\pi k_B T\hbar/l\) (\(l = 0, 1, 2, \ldots\)) are the so-called Matsubara frequencies, the prime near the summation sign in \(l\) means that the term with \(l=0\) is divided by 2, the sum in \(\alpha\) is over two polarizations of the electromagnetic field, transverse magnetic (\(\alpha=TM\)) and transverse electric (\(\alpha=TE\)), and the quantity \(p^{(n)}\) with \(n=1, 2,\) and 3 is defined as

\[
p^{(n)}(i\xi_l, k) = \left[ k^2 + \epsilon^{(n)}(i\xi_l)\mu^{(n)}(i\xi_l)\frac{\xi_l^2}{c^2} \right]^{1/2}.
\]

The reflection coefficients \(r^{(n)}\) on the metallic and dielectric plates (\(n=1\) and 3, respectively) are given by

\[
r^{(n)}_{\alpha l}(i\xi_l, k) = \frac{\epsilon^{(n)}(i\xi_l)\rho^{(n)}(i\xi_l, k) - \epsilon^{(n)}(i\xi_l)p^{(n)}(i\xi_l, k)}{\epsilon^{(n)}(i\xi_l)p^{(n)}(i\xi_l, k) + \epsilon^{(n)}(i\xi_l)p^{(n)}(i\xi_l, k)}
\]

\textbf{3a}
\[ \epsilon^{(n)}_m(i\xi, k) = \frac{\mu^{(2)}(i\xi, k) - \mu^{(3)}(i\xi, k)\rho^{(n)}(i\xi, k)}{\mu^{(2)}(i\xi, k) + \mu^{(3)}(i\xi, k)\rho^{(n)}(i\xi, k)}. \]  

To calculate the Casimir pressure, one should substitute to (1) the values of the dielectric permittivities \( \epsilon^{(n)}_m \) at the pure imaginary Matsubara frequencies \( i\xi \), as well as the values of the magnetic permeability of a ferrofluid \( \mu^{(2)}(i\xi) \). The latter is not equal to unity only at the zero Matsubara frequency \( \Phi(i\xi) \).

In Fig. 1, we present the dielectric permittivities of Au and SiO\(_2\) as a function of the imaginary frequency normalized to the first Matsubara frequency [14][23]. For Au, an extrapolation to the zero Matsubara frequency is performed either by means of the Drude model, \( \epsilon^{(1)}(i\xi) \approx \omega_p^2/(\xi\gamma) \), where \( \omega_p = 1.37 \times 10^{16} \) rad/s is the plasma frequency and \( \gamma = 5.3 \times 10^{14} \) rad/s is the relaxation parameter, or by means of the plasma model \( \epsilon^{(1)}(i\xi) \approx \omega_p^2/\xi^2 \). Numerous experiments on measuring the Casimir interaction demonstrated that the latter extrapolation is experimentally consistent, whereas the former is excluded by the measurement data (see [14], [23], and [24] for review). For SiO\(_2\), \( \epsilon^{(3)}(0) = 3.801 \). [23]

The ferrofluid used in computation below consists of water and the volume fraction \( \Phi \) of magnetite (Fe\(_3\)O\(_4\)) nanoparticles of spherical shape. The dielectric permittivities of these materials along the imaginary frequency axis are also shown in Fig. 1 by the results of [16] and [25], respectively. At zero frequency the dielectric permittivities of water and magnetite are equal to \( \epsilon_m(0) = 81.16 \) and \( \epsilon_m(0) = 29.00 \), respectively (note that for magnetite we omit its conductivity at low frequencies for the reasons explained in [16]). Then, using the data of Fig. 1 for \( \epsilon_m(i\xi) \) and \( \epsilon_m(i\xi) \), the dielectric permittivity of the ferrofluid \( \epsilon^{(2)}(i\xi) \) is obtained from the mixing formula:

\[ \frac{\epsilon^{(2)}(i\xi) - \epsilon_m(i\xi)}{\epsilon^{(2)}(i\xi) + 2\epsilon_m(i\xi)} = \Phi \frac{\epsilon_m(i\xi) - \epsilon_m(i\xi)}{\epsilon_m(i\xi) + 2\epsilon_m(i\xi)}. \]  

Finally, the magnetic permeability of the ferrofluid with \( \Phi = 0.05 \) was found [16] to be equal to \( \mu^{(2)}(0) = 1.24 \) and \( \mu^{(3)}(0) = 2.9 \) for the magnetite nanoparticles with the diameters of \( d = 10 \) nm and \( d = 20 \) nm, respectively.

3. Attractive and Repulsive Casimir Pressure through a Ferrofluid

In the previous work [14], (1) was applied to compute the Casimir pressure through a water- or kerosene-based ferrofluid confined between two similar SiO\(_2\) plates. In this case \( \epsilon^{(1)}(i\xi) = \epsilon^{(3)}(i\xi) \) and the Casimir pressure turned out to be attractive over the entire range of separations between the plates. It was shown that the magnitude of the Casimir pressure may both increase and decrease on the addition of magnetite nanoparticles to a carrier liquid depending on their diameters.

According to the results of [18], the Casimir pressure between Au and SiO\(_2\) plates separated by a kerosene-based ferrofluid remains attractive. The Casimir pressure was investigated [14] as a function of the volume fraction of magnetite nanoparticles and their diameters.

An interesting effect was revealed as to the role of different extrapolations of the dielectric permittivity of Au to the zero Matsubara frequency discussed in Section 2. It was found [16] that, for both two SiO\(_2\) plates and for one Au and one SiO\(_2\) plate, an agglomeration of magnetite nanoparticles into the clusters by two or three results in only
nonessential differences in the values of the Casimir pressure if the extrapolation of the dielectric permittivity of Au is made by means of the Drude model. In the case that the extrapolation is made using the experimentally consistent plasma model, the Casimir pressure may change its sign and become repulsive if some shares of magnetite nanoparticles with a sufficiently large diameter are merged in clusters\cite{17}.

Note that neither the static dielectric permittivity of kerosene $\varepsilon_{\text{ker}}(0)=1.8$ nor the static permittivity of the kerosene-based ferrofluid with $\Phi=0.05$ fraction of magnetite nanoparticles $\varepsilon_{\text{ker,ff}}(0)=2.035$ is sandwiched between the static permittivities of Au and SiO$_2$\cite{16,18}. Because of this, in the three-layer system: Au-kerosene-SiO$_2$, the repulsive Casimir force does not arise (see Section 1). Another situation takes place for water and water-based ferrofluid sandwiched between Au and SiO$_2$ plates. For a water film, it holds

$$\varepsilon^{(1)}(0) > \varepsilon_s(0) > \varepsilon^{(3)}(0).$$

In a similar way, for a water-based ferrofluid with $\Phi=0.05$ volume fraction of magnetite nanoparticles using (4), one obtains

$$\varepsilon^{(1)}(0) > \varepsilon^{(2)}(0) = 77.89 > \varepsilon^{(3)}(0)$$

i.e., in both cases Casimir repulsion is possible.

We have computed the Casimir pressure between Au and SiO$_2$ plates using (1) to (3) for the cases when the intermediate medium is either water or a water-based ferrofluid with $\Phi=0.05$ fraction of magnetite nanoparticles with $d=10$ nm. The computational results for a water intermediate film are shown in Fig. 2. As seen in Fig. 2, the Casimir force is attractive at $a<153$ nm and repulsive at larger separations between the plates. Note that for a water film the computational results do not depend on whether the Drude or the plasma model is used for the extrapolation of the dielectric permittivity of Au down to zero frequency.

For a water-based ferrofluid film with $\Phi=0.05$ volume fraction of magnetite nanoparticles, the computational results are shown in Fig. 3 by the bottom and top lines obtained using the Drude and plasma model extrapolations of the dielectric permittivity of Au, respectively. As shown in Fig. 3, the Casimir pressure through a ferrofluid is repulsive over the entire separation region under consideration, i.e., the presence of magnetite nanoparticles leads to increased repulsion as compared with a water intermediate film.

4. Conclusions

In this paper, we have considered a typical microfluidic system which can be modeled as a thin ferrofluid

\[\text{Fig. 2. Casimir pressure between Au and SiO}_2\text{ plates through a water film shown as a function of the plate-plate separation.}\]

\[\text{Fig. 3. Casimir pressure between Au and SiO}_2\text{ plates through a water-based ferrofluid as a function of the separation, shown by the black and grey lines obtained using the Drude and plasma model extrapolations of the dielectric permittivity of Au, respectively.}\]
layer sandwiched between two material plates. It was underlined that, if the thickness of the ferrofluid layer decreases to below a micrometer, the Casimir force caused by fluctuations of the electromagnetic field comes into play and should be taken into account. For microelectromechanical and optomechanical devices having a vacuum gap between closely spaced surfaces, this fact has been already widely recognized in the literature\[14\][19][26][27].

According to our results, the presence of magnetite nanoparticles in a water-based ferrofluid sandwiched between one metallic and one dielectric plate results in an enhanced effect of repulsion. In fact, at larger separations between the plates, the presence of magnetite particles leads to stronger repulsion. At shorter separations, where the Casimir force through a pure carrier liquid was attractive, the presence of magnetic nanoparticles changes attraction for repulsion. This effect can be used to avoid sticking together of closely spaced elements of ferrofluid-based microdevices. In future, it would be interesting to investigate the effect of enhanced repulsion for different kinds of plate materials, carrier liquids, and magnetic nanoparticles.

References


**Elena N. Velichko** was born in St. Petersburg in 1982. She received the B.S. and M.S. degrees from the Peter the Great St. Petersburg Polytechnic University (SPbPU), St. Petersburg in 2005 and 2007, respectively. She obtained the Ph.D. degree from Saint Petersburg Electrotechnical University, St. Petersburg in 2010. Now she is working with SPbPU as the Director of the Higher School of Applied Physics and Space Technologies at the Institute of Physics, Nanotechnology and Telecommunications, SPbPU. Her research interests include biomolecular electronics and the study of biomolecular processing by laser technologies.
Galina L. Klimchitskaya was born in St. Petersburg in 1946. She obtained the Ph.D. degree in 1975 from St. Petersburg State University, St. Petersburg and the degree of doctor in physical and mathematical sciences from Moscow State University, Moscow in 1985. In 1992, she obtained the academic status of full professor. Now she is working as the Principal Researcher with the Institute of Physics, Nanotechnology and Telecommunications, SPbPU and as the Leading Researcher with the Department of Astrophysics, Central Astronomical Observatory at Pulkovo of the Russian Academy of Sciences, St. Petersburg. She is the author of several books and about 260 papers in the fields of atomic physics, Casimir effect, condensed matter physics, and constraints on non-Newtonian gravity and axion-like particles. She also has taken part as an invited speaker in about 80 international conferences. She is the member of the Editorial Board of Physical Review A.

Elina N. Nepomnyashchaya was born in St. Petersburg in 1992. She received the B.S. and M.S. degrees from SPbPU in 2013 and 2015, respectively. In 2019 she obtained the Ph.D. degree from Saint Petersburg Electrotechnical University. Now she is working as an engineer with the Institute of Physics, Nanotechnology and Telecommunications, SPbPU. Her research interests include studies of nanomaterials by laser technologies.