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NEW RESULTS FOR THE CASIMIR INTERACTION: SAMPLE CHARACTERIZATION AND LOW TEMPERATURE MEASUREMENTS

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We describe our latest results in the separation dependence of the Casimir interaction in the sphere-plane geometry for two Au-coated surfaces. All results are obtained by measuring the change in the resonant frequency of a sensitive microelectromechanical torsional oscillator as the separation between the sphere and the plane is changed. By means of the proximity force approximation, the change in resonant frequency yields the Casimir pressure between two parallel plates at the same separation. We present results for a new sample at room temperature, where the dielectric function has been measured in the 190-825 nm range. We show that the results of the Casimir force in this sample and in previous samples are virtually indistinguishable. Furthermore, the observed differences between measured and tabulated optical properties data do not show any effect on the calculation of the Casimir interaction. We also present results of the measurement of the Casimir force between a sphere and a plane at 300, 77, 4.2 and 2.1 K. While low temperature results are noisier than room temperature ones, precluding a direct exclusion of either the Drude or the plasma model, the average of the measurements coincide at all temperatures.

Keywords: Casimir force; MEMS; Low-temperature measurements.

1. Introduction

The experimental observation of the Casimir interaction between dielectrics has observed an incredible growth in the last thirteen years.[1,2] Among the different observations, two main strategies have been followed: either the groups have measured the interaction between parallel plates[3] (where the signal is larger, but alignment problems are serious), or the interaction between a sphere and a plate[4–10] (which are self aligned, but the signal's strength is reduced due to the decrease in the interacting area). Other approaches, like cylinder-plane[11] and cylinder-cylinder[12] have also been attempted. While most of the experiments have been performed in vacuum with surfaces covered with good conductors (typically Au-covered surfaces), also important progress has been made when the interacting surfaces are dielectrics,[8,13] they are in air,[9] or the dielectrics are immersed in a fluid.[14]

While there is still quite some ground to cover to achieve a complete understanding of the Casimir interaction, and both geometry and composition effects are very important, the most stringent comparisons between experimental data and theoretical models have been achieved in previous experiments from our own group.[7,15,16] In these experiments, performed at room temperature between a Au-coated sapphire sphere and a Au-coated plane, it was observed that the best agreement between theory and experiment is obtained when the material is theoretically described using a generalized plasma model,[16] which takes into account the deep valence electrons, but disregards the dissipation of the conduction electrons. Models that take into account this dissipation, for example a Drude model, have been excluded by the experiment. The reasons behind why a dissipative medium description does not yield the correct answer in a Casimir interaction geometry remain elusive. Several arguments have been brought forward to explain this difference. Among these, the two most recurrent ones are that the intrinsic characteristics of the Au used in the experiment need to be taken into account[17] (instead of the tabular values reported in Ref. 18), and that there are systematics not yet discovered in the experiment that are masking the true result.

In our attempt to elucidate this conundrum, we have performed two new experiments as reported in this paper. In one of them, we performed the experiment at different temperatures, to see if the natural quenching of the phonon-induced dissipation in the Au conductivity was observed. In the other experiment we performed a room temperature measurement of a sample deposited using a different technique. Furthermore, in this last case, the optical properties of the as deposited sample were determined by ellipsometry.

2. Experimental Details

Casimir interaction measurements were performed in a similar fashion as our previous measurements, where the force-sensitive part of our setup is comprised by a microelectromechanical torsional oscillator (MTO). In this paper's room temperature measurements, the position of the sphere and the plate has been swaped. A sapphire sphere of radius $R \sim 150\mu$m was coated inside a thermal evaporator with $\sim$ 10 nm of Cr and $\sim$ 200 nm of Au and then glued to the Au-covered plate of the MTO. Using a combination of mechanical and piezo driven stages, this was brought in close proximity to a [111] Si wafer which was electroplated with 10 nm Cr-200 nm Au. Except for this difference the rest of the setup, as well as the calibrations performed, is identical to the one described in Ref. 15. As a consequence of mounting the sphere on the MTO, a reduction of its resonance frequency from ~ 700 Hz to ~ 300 Hz was observed. A reduction on the quality factor Q of the oscillator was also observed. Q at room temperature and in vacuum ($P < 10^{-6}$ torr) changes from ~ 8000 to ~ 7500 after gluing the sphere. While probably due to the extra stress induced in the torsional serpentine, more work needs to be performed to understand the changes in Q.

Low temperature measurements were performed in a home built cryostat, where the Au-coated sphere is positioned on top of the Au-coated MTO. The coarse mechanical actuation was performed from the outside, and a piezo-tube and home built slip-stick piezo driven stages were used to provide the fine positioning inside the cryostat. Once the coarse positioning was achieved, the external driving rods were decoupled, and the inner part of the cryostat remained suspended from springs and magnetically damped to reduce vibrations. The inner part of the system was kept at a low He pressure, on the order of 10^{-3} torr, to homogenize the temperature. While the system consists of a sensor and a heater, allowing in principle for temperature dependent measurements, it was found that the thermal drift was so severe that it precluded any measurements where the separation was kept constant and the temperature was changed. Instead, all the calibrations and measurements were performed at constant temperature, provided by the fixed points of liquid nitrogen, liquid helium, and the lambda point of helium. While room temperature measurements for this sample were performed in a different system, it is worth mentioning that room temperature measurements performed in this system with no cryogenic liquids present, showed an increase on the experimental noise on the order of a factor of 2.5. This points out that while the cryostat is not as well isolated from vibrations as the table-top system, the increase in the experimental noise observed at low temperatures is associated with vibrations arising from within the cryostat.

In all our measurements of the Casimir interaction, the MTO's resonance frequency $\omega_{\text{res}}(z)$ was monitored as the separation z between the sphere and the plate is changed. In the linear regime (i.e. small amplitude of oscillation), $\omega_{\text{res}}(z)$ is given by

$$\omega_{\text{res}}^2 = \omega_o^2 \left[1 - \frac{b^2}{I\omega_o^2}\frac{\partial F_C}{\partial z}\right] \tag{1}$$

where ω_o is the MTO's resonant frequency when no interaction is present, b is the lever arm between the point of interaction and the torsional axis, I is the MTO's moment of inertia, and F_C is the Casimir force between the sphere and the plane. By means of the proximity force approximation[a]

$$\frac{\partial F_C}{\partial z} = 2\pi R P_C(z), \tag{2}$$

[a] We consider throughout the paper that the attractive Casimir interaction has a positive sign.

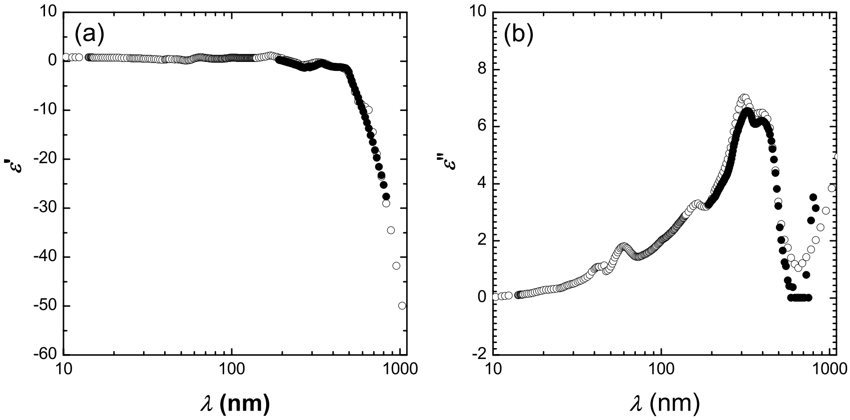

Fig. 1. The filled circles (●) show (a)Obtained real (ε') and (b) imaginary (ε'') parts of the dielectric function from the ellipsometry measurements, between 190 and 825 nm. Tabulated data are displayed as open circles (○).

where $P_C(z)$ is the Casimir force per unit area between two infinite plates separated by a distance z.

3. Results

3.1. *Optical properties of the sample used*

The ellipsometric results for the dielectric function obtained on the Au electroplated Si wafer are shown in Fig. 1. These results are compared with tabulated data. While Fig. 1 shows the frequency dependence for both the real and imaginary parts of the dielectric function, when calculating the Casimir interaction using Lifshitz approach,[19] only the imaginary part is needed. This comes about because in Lifshitz approach the material information enters through an evaluation of its dielectric function along imaginary frequencies, $\varepsilon(i\omega)$, which is given by[20]

$$\varepsilon(i\omega) = 1 + \frac{2}{\pi}\int_0^\infty \frac{x\varepsilon''(x)}{x^2 - \omega^2}dx. \tag{3}$$

Hence, to compare the dielectric function evaluated at imaginary frequencies from tabulated data and from our sample, we first calculated the results using Eq. (3) where tabulated data was used between 10^{14} and 10^{19} rad/s. At lower frequencies a Drude model with a value of the plasma frequency $\omega_P = 9$eV and a relaxation parameter $\gamma = 35$ meV was used. For frequencies above 10^{19} rad/s, $\varepsilon''(\omega) \equiv 0$. For the electrodeposited sample, we repeated the same calculation, but tabulated data for ε'' was replaced by our measurements in the relevant frequency range, i.e. between 2×10^{15} and 10^{16} rad/s. The results obtained are shown in Fig. 2.

Unfortunately, the range of frequencies covered by our measurements of the dielectric properties does not seem to be large enough to provide a significant effect

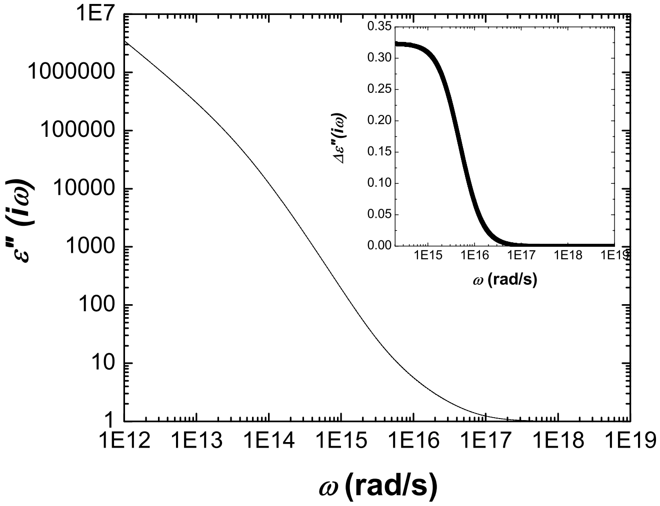

Fig. 2. Dielectric function along the imaginary frequency axis, as obtained from Eq. (3). Results from tabulated data and our sample are shown. They are not distinguishable in the plot. Inset: difference between both calculations. Note the linear vertical axis.

Table 1. Values of $f_o = \omega_o/(2\pi)$, Q, and the noise δP_C at 300 nm at the different temperatures.

Temperature (K)	f_o (Hz)	Q	δP_C (mPa)
2.1	785.01	11345	22
4.2	766.28	11355	63
77.0	733.33	10222	56
296.5	702.103	7325	2

on the calculation of the Casimir force. When the Lifshitz expression is used to calculate the Casimir interaction, the difference in P_C obtained when using tabulated data for both the plate and the sphere, or our optical data for the plate and tabulated data for the sphere is about an order of magnitude smaller than the experimental error on P_C. Measurements of the Casimir interaction, however, can be compared between two sets of data. In Fig. 3 we plot the Casimir pressure as a function of separation, $P_C(z)$ for the sample reported in Ref. 16, and the electrodeposited sample. As observed, differences between both data sets are in general smaller than the experimental error. The difference between data sets was obtained at each separation where P_C was measured for the new sample. The values of P_C at these separations for the previously measured sample were obtained by linear interpolation.

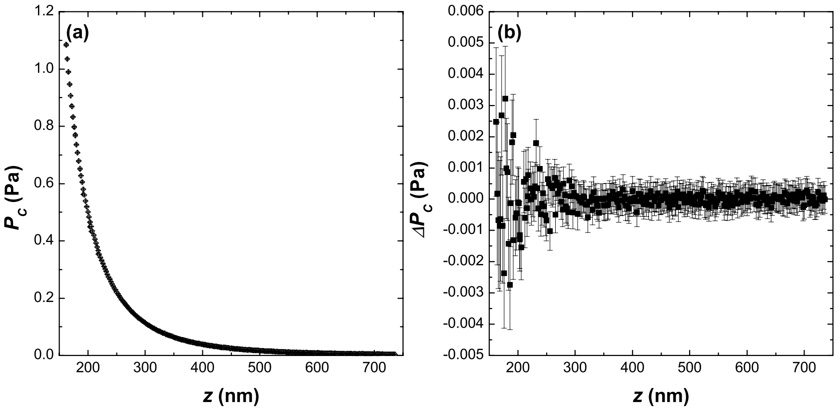

Fig. 3. (a)Measured Casimir pressure as a function of separation for the current run (•) and previously published data (∘). (b) Difference between both sets of data. The error bars represent the 95% confidence level in the experimental measurements, both in position and pressure.

3.2. *Low temperature measurements*

When cooling down the MTO, an increase on both ω_o and Q are observed, as shown in Table 1. More relevant to this work, however, are the low temperature measurements $P_C(z)$, which are shown in Fig. 4. It is evident from the data that the noise is greater at low temperatures, being the largest at the 77 and 4.2 K. When the He bath is pumped below its λ-point the noise decreases, as shown in Table 1, where we report the noise at different temperatures and 300 nm. The

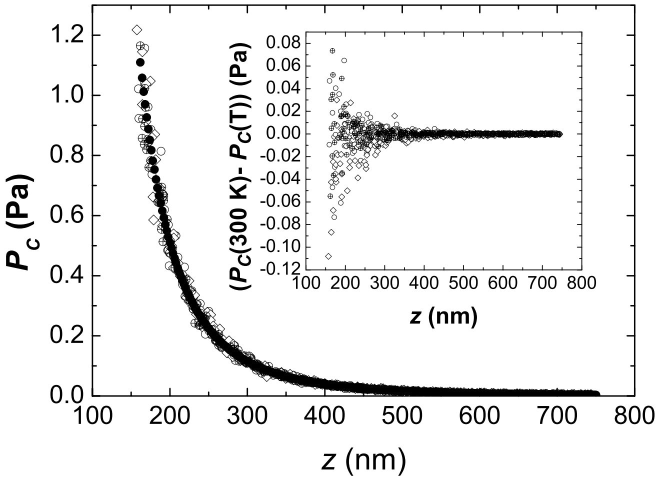

Fig. 4. $P_C(z)$ at different temperatures. (•) T = 300 K, (∘) T = 77 K, (⋄) T = 4.2 K, and (⊕) T = 2.1 K. Inset: $P_C(z, 300K) - P_C(z, T)$, where T = 77 (∘), 4.2 (⋄), and 2.1 K (⊕).

relative increase of the noise with respect to the room temperature measurements are similar for other separations as well. While it is not shown in Fig. 4, when the sample is measured at room temperature inside the cryostat, an increase in the noise of about a factor of 2.5 is observed when compared to $\delta P_C(300nm, 300K)$. From these observations we conclude that although the vibration isolation of the cryostat is not as good as in the room temperature system, the main source of noise is due to internal vibrations when the cryogenic liquids are present, most likely due to their boiling. The reduction in the noise when below the λ-point seems to emphasize the importance of cryogenic liquids bubbling. Long term measurements to try to alleviate the random noise induced by vibrations are not possible, since the change in the cryogenic liquid levels induce a temperature gradient in the two-color fiber interferometer, producing a time dependent change in its calibration. This is a result of the different temperature dependance of the fiber's index of refraction at the two wavelengths employed. For this reason, the separation error is also larger at low temperatures.

In spite of the many difficulties presented in the first low temperature measurements of the Casimir interaction, we would like to emphasize that the average P_C at any separation seems to coincide for all investigated temperatures. This is better seen in the inset, where we have subtracted from the experimental values at 300 K the experimental values at the other measured temperatures. The subtraction was performed at the separations measured at low temperatures, and the room temperature value was found by linear interpolation.

4. Conclusions

In conclusion, we have performed two sets of measurements which, while promising, are not conclusive. In one experiment, we observed a clear difference in the optical constants between our sample and tabulated data. Over the range of frequencies of the optical data measurements, this does not translate in a significant effect on the calculated $P_C(z)$. Along the same lines, the observed difference in the measured $P_C(z)$ between samples made by different methods is smaller than the experimental error. On the other experiment, for our measurements of P_C at different temperatures, we were not able to see any difference between the room temperature and low temperature measurements, due in large part to the significant increment in vibrational noise in our low temperature setup. We are hopeful that an improvement on the experimental setup will yield a definite experimental answer to the role played by dissipation in the Casimir interaction.

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