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Modeling of the intermolecular Force-Induced Adhesion in Freestanding Nanostructures Made of Nano-beams

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Abstract

Among the intermolecular interactions, the Casimir and van der Waals forces are the most important forces that highly affect the behavior of nanostructures. This paper studied the effect of such forces on the adhesion of cantilever freestanding nanostructures. The nanostructures are made of a freestanding nano-beam which is suspended between two upper and lower conductive surfaces. The linear spring model was applied to derive the elastic force. The Lumped Parameter Model (LPM) was used to obtain constitutive equations of the systems. The maximum length of the nano-beam which prevents the adhesion was computed. Results of this study are useful for the design and development of miniature devices.

Keywords: Adhesion, Casimir force, van der Waals force, Freestanding nano-beam, Lumped Parameter Model (LPM).

1. Introduction

The beam-type nanoactuators are the most common components in developing nanostructures [1-7]. It is well established that the behavior of nanostructures is influenced by intermolecular interactions. When the initial gaps between the components of actuators are typically below several ten nanometers, the force between surfaces can be described by van der Waals attraction; otherwise, the force between surfaces can be considered as the Casimir force [7–9]. As the dimensions of nanostructures are reduced to the nanometer scale, the intermolecular forces can induce adhesion in nanostructures. In other word, movable elements of nanodevices may stick together due to the strong attractive intermolecular forces. The intermolecular forces can also induce undesired adhesion in freestanding nanostructures during the fabricating and manufacturing stages. Therefore, these forces should be taken into account in the design, manufacture and operation of freestanding nanoscale devices [10, 14].

A simple method to investigate the adhesion of nanostructures is lumped parameter models. A one-degree-of-freedom lumped parameter model has been proposed by Lin and Zhao [10, 11] to scrutinize stiction of nanostructures in the presence of electrostatic and Casimir attractions. Abadyan et al. [15] have used the homotopy perturbation to investigate the stiction parameters of cantilever beam-type actuators under Casimir forces. The influence of surface effect and van der Waals force on pull-in voltage of rotational nano–micro mirror has been investigated by Beni et al. [4]. Soroush et al. have employed the Adomian decomposition to investigate the instability of cantilever nano-actuators under dispersion (van der Waals and Casimir) forces by considering their range of application [14]. The effects of size dependence and dispersion forces on the pull-in instability of electrostatic cantilever nanostructures using modified couple stress theory has been simulated by Abdi et al. [16]. All the above-mentioned works have focused on modelling the instability in structures with two planar electrodes. However, very limited works have been dedicated to modelling the behaviors of the nanostructures that consist of three electrodes. This type of nanostructures has been proposed by researchers due to their promising electromechanical performance [17-19].

Accordingly, in the present study, the effect of the intermolecular forces on the adhesion of freestanding three-electrode nanostructures is investigated. The structures have been made of a nano-beam electrode suspended between two other planar electrodes.

2. Theoretical Model

Fig.1 shows the typical cantilever three-electrode nanostructure made of a movable nano-beam suspended between two fixed planes. The nano-beam can deflect up/down towards each of the fixed planes.

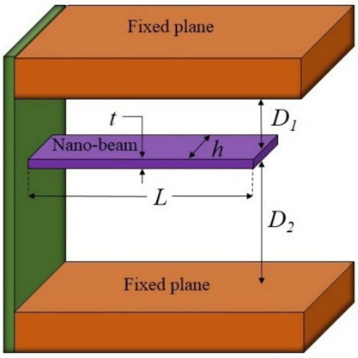

Fig. 1. The schematic representation of typical cantilever three-electrode nanostructure.

The length, width and thickness of the nano-beam are L, w, and t, respectively. The initial gap between the nano-beam and upper plane is D_1, and the initial separation between the lower plane and the nano-beam is D_2.

2.1 The van der Waals Force

The van der Waals energy between a beam and flat surface is [20]

$$E = -\frac{AwL}{12\pi D^2}, \tag{1}$$

By considering the deflection of the beam and by replacing D1 with D1–y and D2 with D2+y, the van der Waals forces, can be defined from (2) as

$$F_{vdW1} = \frac{AwL}{6\pi(D_1 - y)^3}, \tag{3-a}$$

$$F_{vdW2} = \frac{AwL}{6\pi(D_2 + y)^3}. \tag{3-b}$$

where F_{vdW1} and F_{vdW2} denote the vdW attraction between the nano-beam/upper plane and nano-beam/lower plane respectively.

2.2 The Casimir Force

The Casimir energy between a beam and flat surface is [21-23]

$$E_{Cas} = -\frac{\pi^2 \bar{h} c w L}{720 D^3}, \tag{4}$$

where $\bar{h}$ is the reduced Planck's constant (Planck's constant divided by 2π) and c = 2.998×108 m/s is the speed of light. By differentiating the energy, the Casimir force can be written as

$$F_{Cas} = \frac{\pi^2 \bar{h} c w L}{240 D^4}, \tag{5}$$

Now by considering the deflection of the Beam, the Casimir forces, can be obtained from (5) as

$$F_{Cas1} = \frac{\pi^2 \bar{h} c w L}{240(D_1 - y)^4}, \tag{6-a}$$

$$F_{Cas2} = \frac{\pi^2 \bar{h} c w L}{240(D_2 + y)^4}. \tag{6-b}$$

where F_{Cas1} and F_{Cas2} denote the Casimir force between the nano-beam/upper plane and nano-beam/lower plane, respectively.

2.3 Elastic force

The linear spring model is used to simulate the elastic energy (E_{elas}). This model assumes the uniform intermolecular forces along the length of the nano-beam as shown in Fig. 2.

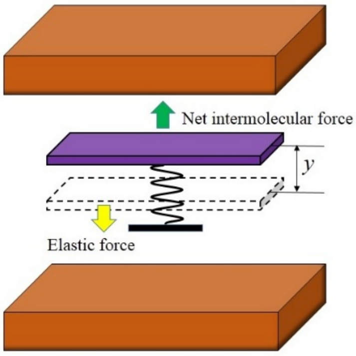

Fig. 2. Schematic representation of LPM for a nanostructure.

According to this model, the elastic energy can be written as

$$E_{elas} = -\frac{1}{2} K w^2, \tag{7}$$

where K is the effective spring constant. By using a 1D Lumped Parameter Method (LPM), the spring constant can be derived as [10]

$$K = \frac{8 E_{eff} I}{L^3} \quad \textit{for a cantilever nano-beam}, \tag{8}$$

where E_{eff} is the effective Young's modulus, I is the cross-sectional moment of inertia and $E_{eff}\,I$ is the effective flexural rigidity of the nano-beam. By differentiating the energy, the elastic force can be obtained

$$F_{elas} = -\frac{8 E_{eff} I y}{L^3}. \tag{9}$$

3. Solution method

In order to derive the governing equation of the nanostructure, the following equilibrium condition is considered:

$$F_{net} = F_{elas} + F_{\text{int}1} + F_{\text{int}2} = 0, \tag{10}$$

By substituting relations (3-a), (3-b) or (6-a), (6-b) and (9) into Eq. (10), the governing equation of the systems is derived as

For vdW force,

$$\frac{8 E_{eff} I y}{L^3} = \frac{A w L}{6\pi}\left[\frac{1}{(D_1 - y)^3} - \frac{1}{(D_2 + y)^3}\right]. \tag{11-a}$$

For Casimir force,

$$\frac{8E_{eff}Iy}{L^3}=\frac{\pi^2\bar{h}cwL}{240}\left[\frac{1}{(D_1-y)^4}-\frac{1}{(D_2+y)^4}\right]. \qquad (11\text{-b})$$

The LPM only simulates the tip point of the cantilever nano-beam; thus, in Eq. (11), y is identical to y_{tip}. Finally the dimensionless nonlinear equation for the system is obtained as

For vdW force,

$$\gamma=\frac{8\bar{y}_{tip}}{\dfrac{1}{\left(1-\bar{y}_{tip}\right)^3}-\dfrac{1}{\left(\alpha+\bar{y}_{tip}\right)^3}}, \qquad (12\text{-a})$$

For Casimir force,

$$\gamma=\frac{8\bar{y}_{tip}}{\dfrac{1}{\left(1-\bar{y}_{tip}\right)^4}-\dfrac{1}{\left(\alpha+\bar{y}_{tip}\right)^4}}, \qquad (12\text{-b})$$

The following dimensionless parameters were used to obtain Eqs. (12)

$$\alpha=\frac{D_2}{D_1}, \qquad (13\text{-a})$$

$$\bar{y}_{tip}=\frac{y_{tip}}{D_1}, \qquad (13\text{-b})$$

$$\gamma=\begin{cases}\dfrac{AwL^4}{6\pi E_{eff}ID_1^4} & \text{for vdW force}\\[2ex] \dfrac{\bar{h}c\pi^2wL^4}{24oE_{eff}ID_1^5} & \text{for Casimir force}\end{cases}, \qquad (13\text{-c})$$

Note that the parameter γ denotes the dimensionless value of the intermolecular attraction. Any decrease in gap (D_1) as well as any increase in width (w) or length (L) leads to increasing in γ value.

3.1 Adhesion Analysis

The equilibrium is stable with $\partial\gamma/\partial\bar{y}<\infty$. The critical state occurs when $\partial\gamma_{cr}/\partial\bar{y}=\infty$. Considering any given γ, where $\gamma \leq \gamma_{cr}$, one can find solutions for $\hat{w}$. However, when $\gamma > \gamma_{cr}$, no solution exists for $\hat{w}$. This means that the adhesion occurs and the nano-beam collapses onto the fixed substrate [10-13]. The values of γcr and the corresponding nano-beam critical deflection, $\bar{y}_{cr}$, can be determined by plotting the dimensionless intermolecular attraction parameter, γ, vs. the dimensionless deflection at the tip point of the nano-beam.

4. Results and Discussion

4.1 Adhesion analysis

Considering the vdW force and Casimir force, Figs. 3 and 4 show the relation between the parameter γ and the tip displacement of the cantilever nano-beam respectively. As shown, when the parameter γ reaches its critical value γcr, the tip deflection of the nano-beam reaches its maximum value $\bar{y}_{cr}$. From physical point of view, the net intermolecular attraction overcomes the elastic resistance of the nano-beam; hence, the nano-beam collapses and adheres to the upper plane.

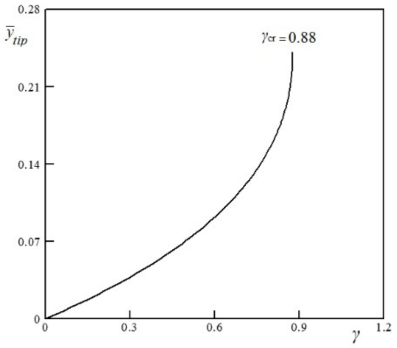

Fig.3. The variation of the tip displacement of the cantilever nano-beam versus γ for the vdW force using α = 2.

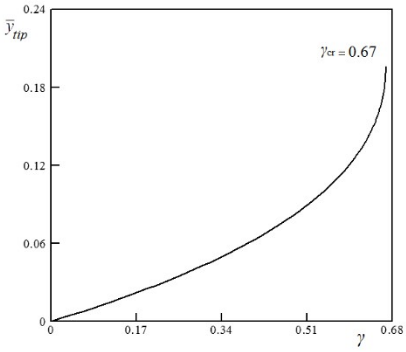

Fig.4. The variation of the tip displacement of the cantilever nano-beam versus γ for the Casimir force using α = 2.

4.2 Impact of geometry of the structures

In order to examine the impact of geometry on behavior of the system, variation of the critical value of the intermolecular parameter, γcr, as a function of the geometrical parameter, α, are presented in Figs. 5 and 6 by considering the vdW and Casimir forces, respectively. Note that α represents the ratio between the D1 and D2.

As shown below, decreasing α parameter increases the critical value of Casimir force. This means that reduction of the difference between D_1 and D_2 can stabilize the structure because the attractive effect of the upper surface neutralizes the attractive effect of the lower surface.

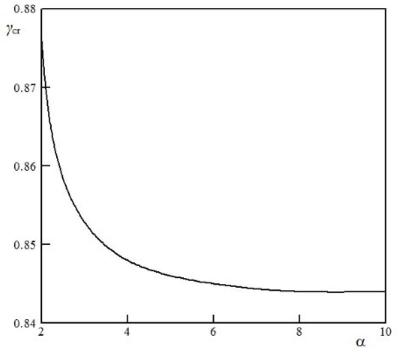

Fig.5. The variation of the parameter γcr versus the parameter α for the vdW force.

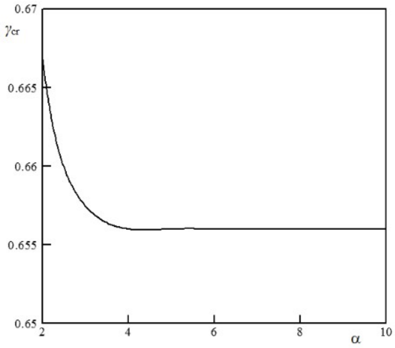

Fig.6. The variation of the parameter γcr versus the parameter α for the Casimir force.

4.3 Detachment length and minimum gap

As mentioned earlier, the movable elements of the nanostructures (nano-beam) may stick to the fixed upper plane due to the strong attractive intermolecular forces. It leads to undesired adhesion in freestanding nanostructures during the fabricating and manufacturing stages. Therefore, these forces should be taken into account in the design, manufacture and operation of freestanding nanoscale devices.

In this stage, we determine the detachment length and minimum gap of the nanostructures which are very important parameters in design nanostructures. The detachment length, L_{max}, is the maximum length of the nano-beam that the nano-beam does not stick to the fixed plane [10-13]. On the other hand, if the length of nano-beam is known, there is a minimum gap, D_{1min}, which prevents stiction between the nano-beam and the plane.

In order to determine the detachment length and minimum gap one can use the Eq. (13-c). By substituting the value of γcr into the definition of γ (in Eq. (13-c)), the values of L_{max} and D1min can be easily computed. Note that in general, the value of detachment length and minimum gap is a function of geometrical parameters and elastic constants of the nano-beam. As a case study, Table 1 shows the comparison between the L_{max} and D_{1min} values obtained for a typical nanostructures (α=2).

Table1. Critical value of intermolecular parameter and corresponding formulas for computing detachment length (L_{max}) and minimum gap (D_{1min}) of freestanding nanostructures with α=2.

	γ_{cr}	L_{max}(m)	D_{1min}(m)
vdW	0.88	$7.589\times10^{4}D\left(\frac{E_{eff}I}{w}\right)^{0.25}$	$1.318\times10^{-5}L\left(\frac{w}{E_{eff}I}\right)^{0.25}$
Casimir	0.67	$4.765\times10^{6}\left(\frac{E_{eff}ID^{5}}{w}\right)^{0.25}$	$4.545\times10^{-6}\left(\frac{L^{4}w}{E_{eff}I}\right)^{\frac{1}{5}}$

5. Conclusion

The nomenclature herein, linear spring model was applied for simulating the effect of intermolecular attractions on the Adhesion of nano-beam-made nanostructure with three electrodes. It is found that:

1- When the intermolecular forces exceed the critical value, it overcomes the elastic resistance of the nano-beam; hence, the nano-beam becomes unstable and adheres to the upper plane.

2- The detachment length and minimum gap parameters, which are critical in the design and fabrication of the nanostructure, were determined

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