SERBIATRIB '09

Serbian Tribology Society

11th International Conference on Tribology

University of Belgrade Mechanical Engineering Faculty

Belgrade, Serbia, 13 -15 May 2009

ELECTROSTATIC GECKO MECHANISM

Thomas Prevenslik
Consultant, Berlin, Germany, e-mail: tribology@nanoqed.net

Abstract: *Nanoparticles (NPs) are ubiquitous and attach to all surfaces. Nature by providing the gecko with toe-hairs to detach NPs from surfaces has allowed electromagnetic (EM) radiation to be produced that by the photoelectric effect allows the gecko to walk on walls and ceilings by electrostatic attraction. Since attached NPs are a part of macroscopic surfaces, the atoms in the attached NPs are not under EM confinement and are allowed by quantum mechanics (QM) to have full thermal kT energy. But NPs in the detached state differ in that they are under EM confinement at vacuum ultraviolet (VUV) levels that by QM are restricted to vanishing kT energy and specific heat, and therefore the full kT energy remaining cannot be conserved by an increase in temperature. Since NPs have EM confinement frequencies at VUV levels, and since the EM confienement frequency is the lowest frequency allowed in the NPs, the low frequency excess kT energy is frequency up-converted to the VUV by quantum electrodynamics (QED). Conservation is completed by the NPs emitting a burst of VUV radiation that by the photoelectric effect charges the walls and ceiling positive and the toe-hairs negative, therby allowing the Gecko to walk on walls and ceilings by electrostatic attraction.*

Keywords: *Geckos, biotribology, electrostatics.*

1. INTRODUCTION

Since Aristotle, geckos have attracted the curiosity of mankind by running along smooth vertical walls and across ceilings. But not until 1872 was the first documented study [1, 2] reported of the mechanism by which geckos can walk on walls and ceilings.

The gecko's secret for walking [3] is the structure of their toe that comprise a uniform array of setae of β-keratin hair bristles. Setae are approximately 100 microns long and 5 microns in diameter. Each setae tip branches into about 1000 spatulae having a flattened triangular end about 200 nm on a side with 10-30 nm edges.

Paradoxically, the setae are not oriented normal to the toes as would be expected to achieve the high extension stiffness necessary to support the gecko weight. Instead, the setae are aligned in the manner of a cantilever parallel within 30 degrees of the wall or ceiling surface. Lateral loading therefore is limited by the peeling of the spatulae from the surface. Gecko weight is carried [3-7] with the spatulae tipped setae held to the wall or ceiling by van der Waals (vdW) forces.

1.1 Difficulties with vdW Mechanism

The vdW interaction was first formulated [8] to explain short range intermolecular attractive forces between atoms and molecules in gases separated by a few angstroms. Simulations [3] show the vdW force necessary to support the gecko requires the separation distance of less than 1 nm over the full spatulae area of 200 sq. nm. For rough surfaces, this is highly unlikely.

It therefore follows nature [4] would provide setae in the form of flexible cantilevers to allow contact with roughened surfaces, but certainly not to carry gecko weight. Obviously, nature had another function in mind for the gecko setae.

1.2 Alternative Mechanisms

Alternatives to the vdW force as the mechanism by which the gecko is held to walls and ceilings have generally [3] been dismissed.

Electrostatic attraction [2] is generally thought not applicable to geckos based on experiments [9] that showed the gecko to walk normally in the presence of ionized air. This is correct if the gecko as a whole is charged say, negative and the wall or ceiling positive, for then the surrounding ionized air discharges the potential difference between the gecko and surface. However, ionized air would not cancel the charge that develops at the instant NPs detach by the gecko's toe hairs.

> But what electrostatic mechanism could be instantly activated between the gecko's toe and the wall?

One such mechanism is the Sandia electrostatic chuck (ESC) used [10] to handle semiconductor wafers. But the ESC modified for active magnetic hairs and adapted [11, 12] to shoes allowing man to mimic the gecko and walk up steel utility poles. The claim [11] is made that magnetic hairs are "gecko inspired." But the concept of active magnetic hairs is far removed from the passive β karatin hairs that nature chose for the gecko's toes.

1.3 Charging by NPs

Gecko charging by NPs is analogous with the theory [13, 14] to unify all of static and atmospheric electricity with NPs. Indeed, the early Greek discovery that static electricity may be produced by rubbing amber rods with a cloth may be understood [13] by the NPs that by rubbing detach from the surface of a amber rod.

Static electricity from detached NPs may also be related to the ability of the gecko to walk on inverted surfaces. Unlike amber rods where the detachment of NPs takes some rubbing force, the dust NPs from the atmosphere that settle on walls and ceilings are loosely bound. In this regard, Nature has provided the gecko with submicron spatulae tipped toe-hairs that in the manner of a nano-brush may detach NPs from these surfaces, although the larger micron particles (MPs) may be more difficult to detach.

1.4 Walking on a Carpet

Gecko charging by NPs finds similarity with the electrical shock you receive from the NPs you detach from carpet fibres with your shoes in walking across a room [13, 14]. Atoms in NPs attached to micron sized carpet fibres are in effect a physical extension of a macroscopic body having full thermal k*T* energy.

Under the action of your shoe, the NPs detach from the carpet fibres. NPs in the detached state have EM confinement frequencies in the VUV that by QM requires the atoms to have vanishing *kT* energies. Therefore, the NPs have excess *kT* energy, but the excess cannot be conserved by an increase in temperature because the NPs under VUV confinement also have vanishing specific heat. Since the NPs have EM confinement frequencies at VUV levels, and since the EM confinement frequency is the lowest frequency allowed in the NPs, the low frequency *kT* energy is frequency up-converted by QED to VUV levels allowing the NPs to emit a burst of VUV radiation.

The VUV radiation charges the hard rubber soles on your shoes positive relative [15] to say, a polyester carpet. Step by step, the NP charging is repeated with your shoes accumulating positive charge. Discharge occurs by the well known electrical shock upon touching the doorknob.

Charging by NPs with carpets accumulating charge step by step differs from that by geckos where charge is discharged after every step.

1.5 Electrostatic Charging Mechanism

The electrostatic gecko mechanism assumes the presence of the ubiquitous NPs on walls or ceilings. Gecko walking is illustrated in Fig. 1.

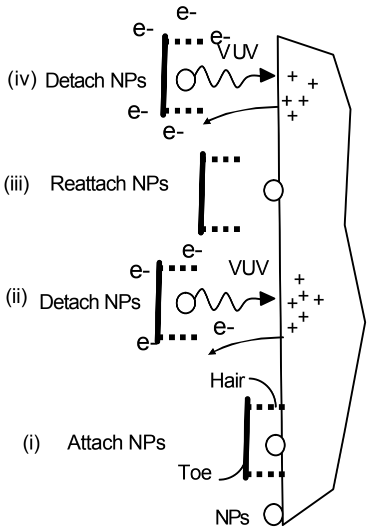

Figure 1. Electrostatic Gecko Mechanism
VUV Radiation as NPs Detach from Surface

(i) Prior to gecko's approach NPs are shown attached to the wall, although some NPs attach to the toe-hairs. Openings between spatulae are submicron to allow NP attachment, but MPs are rejected.

(ii) By stepping on the walls or ceiling, NPs are detached by the toe-hairs. The NPs in the detached state emit VUV radiation. In the tribo-series [15] glass and ceramic surfaces charge positive while the toe-hair comprised of β-keratin acquires a negative charge. An electrostatic force is induced that attracts the gecko's toe-hairs along with toe and foot to the surface. Except for Teflon®, friction in combination with the attractive electrostatic force supports the gecko against gravity.

(iii) Recovery of kT energy is prompt upon reattachment of the NPs to the surface and toe-hairs.

(iv) NP detachment once again emits VUV radiation to increase the electrostatic attraction of the gecko's foot to the surface. By the gecko not moving his toes, the electrostatic force ceases allowing his foot to be easily lifted for the next step. Steps (iii) and (iv) may be repeated many times.

2. THEORY

Gecko toe-hairs are shown to provide the important function of acting as a nano-brush to detach the NPs from a wall or ceiling. NPs emit VUV radiation upon being detached from walls and ceilings that by the photoelectric effect charges the surface positive while removing electrons to charge the gecko toe and gecko hairs negative, thereby holding the gecko to the surface by electrostatic attraction as depicted in Fig. 2.

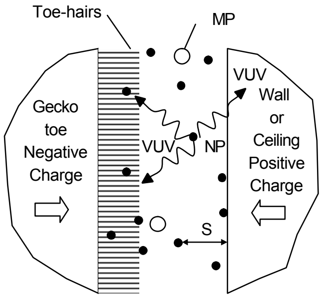

Figure 2 Gecko charging detaching NPs

2.1 QM Restrictions

QM restricts the *kT* energy of atoms depending on the EM confinement wavelength l of the NPs. At 300 K, the Einstein-Hopf relation [16] for the harmonic oscillator gives the *kT* energy as shown in Fig. 3.

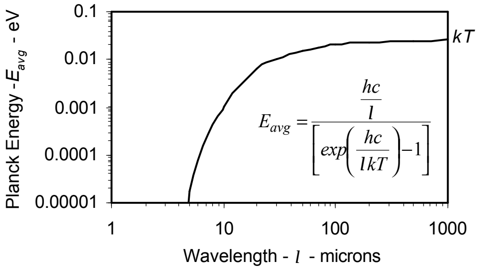

Figure 3 Harmonic Oscillator at 300 K
h is Planck's constant, and *c* the speed of light

Prior to being detached by the gecko's toe-hairs, the atoms in the NPs attached to the surface are not under EM confinement and have full *kT* energy; whereas, atoms in detached NPs under EM confinement have vanishing *kT* energy. Fig. 2 shows full *kT* energy ~ 0.0258 eV for l > 100 microns and $kT \sim 1\text{x}10^{-5}$ eV at EM confinement of l ~ 5 microns. Hence, NPs under EM confinement at VUV wavelengths l < 0.050 microns have vanishing small $kT << 1\text{x}10^{-5}$ eV.

2.2 EM Confinement Frequencies

For NPs having $D << l$, the EM confinement is analogous [14] to the QM analogy of creating photons of wavelength l by supplying EM energy to a QM box with walls separated by l / 2. For NPs of diameter *D* and refractive index *n,* the EM confinement frequency *f* and Planck energy E_P,

$$f = \frac{c}{l},\ l = 2nD \text{, and } E_P = \frac{hc}{l} = \frac{hc}{2nD} \qquad (1)$$

2.2 Vanishing Specific Heat

Classical heat transfer conserves absorbed EM energy by an increase in temperature, but is not applicable to NPs because of QM restrictions on thermal kT energy. Equivalently, the specific heat of NPs may be said to vanish.

In the Einstein and Debye formulations of specific heat, the phonons carry heat as the atoms vibrate in the lattice. However, the approach here differs in that optical modes in the NP consistent with a spherical box of photons are of interest. Taking the Einstein-Hopf relation, the specific heat *C* given by ¶*U/*¶*T*, the dimensionless specific heat *C** is,

$$C^* = \frac{C}{3Nk} = \frac{\left(\frac{hc}{lkT}\right)^2 exp\left[\frac{hc}{lkT}\right]}{\left[exp\left(\frac{hc}{lkT}\right)-1\right]^2} \qquad (2)$$

At 300 K, *C** vanishes for l = *2nD* < 5 microns. For n_r =1.2, the absorbed EM energy for *D* > 2 microns is conserved by a temperature increase while EM emission occurs for *D* < 2 microns. Similarity is found with vanishing specific heat *C** in thin films [17].

2.3 NP Force

Upon detachment, atoms in NPs have the same *kT* energy as those in the surface. The energy *U* is,

$$U = \frac{p}{6}\left(\frac{D}{\Delta}\right)^3 3kT = \frac{p}{2}\left(\frac{D}{\Delta}\right)^3 kT \qquad (3)$$

where, *D* is the cubic spacing between NP atoms at solid density, *D* ~ 0.3 nm. Lacking specific heat, the NP conserves the energy *U* in a burst of VUV radiation that by Einstein's photoelectric effect electrifies the surroundings.

The charge q is,

$$q = N_P Ye = \frac{U}{E_P} Ye = pkT\left(\frac{D}{\Delta}\right)^3 \frac{n_r D}{hc} Ye \qquad (4)$$

where, N_P is the number of QED photons induced in the NPs at Planck energy E_P.

The charge q produces an electric field F between the gecko toe and the surface. The NP force F_{NP} is,

$$F_{NP} = qF < qF_{BD} \qquad (5)$$

where, F_{BD} is the breakdown field F_{BD} in air, $F_{BD} \sim 3\text{x}10^6$ V/m. Taking $n_r = 1.2$, $l = 240$ nm and $E_P > 5$ eV where most materials [18] have yields Y ˜ 0.1 electrons/VUV photon, the upper bound F_{NP} is shown with Planck energy E_P in terms of NP diameters D in Fig. 4.

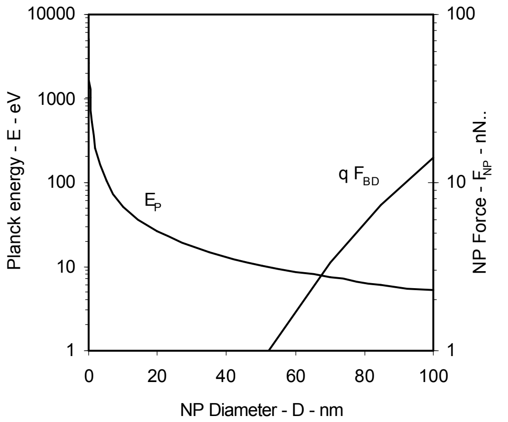

Figure 4. Upper Bound Electrostatic NP Force

The peak NP force is observed to occur at D = 100 nm, beyond which the NP force is not shown because the yield Y rapidly diminishes. The peak charge $q \sim 4.8$ fC/NP, and therefore the force F_{NP} is upper bound at $F_{NP} \sim 15$ nN.

The total electrostatic force F_{ES} from number N_{NP} of NPs is,

$$F_{ES} < N_{NP} qF_{BD} \qquad (6)$$

For a gecko weighing 70 g, the necessary force F_{ES} is about 0.68 N that requires more than 45 million NPs. At close packed spacing the maximum number of 100 nm NPs is $D^{-2} \sim 10^{14}$/ sq. m. Since all 4 gecko feet have an area [3] of 454 mm^2, and since the maximum number of NPs available is about $4.5\text{x}10^{10}$, gecko walking only requires about 0.1% of the maximum possible NPs which appears reasonable.

2.4 Available NPs and Recovery of kT Energy

The number of NPs necessary to support the gecko may not be available on all surfaces on which the gecko chooses to walk. The 4 gecko feet having an area of 454 mm^2 [3] with 14,400 setae/mm^2 corresponds to about 6.5 million setae. For the 45 million NPs necessary to support a 70 g gecko would require about 8 NPs/setae.

To provide more electrostatic force, the gecko may simply move his toes to detach more NPs provided the NPs can promptly reattach elsewhere. Fig. 2 shows a typical NP located in the gap between the toe-hairs and support structure. The time t for the NP to move the distance S is,

$$t = \sqrt{\frac{m}{F_{NP}} S} \qquad (7)$$

where, m is the NP mass. At the setae tip, the spacing S between spatulae is less than 10 micron. Taking dust to be silicon, the mass m of a D = 100 nm NP is, $m \sim 1.2\text{x}10^{-18}$ Kg. For $F_{NP} \sim 15$ nN, the time t to reattach is, $t \sim 28$ ns. Compared to the gecko moving his toes reattachment is small.

3. DISCUSSION

The proposed gecko electrostatic mechanism based on NPs redefines the function of gecko setae and spatulae from that of load carrying capability by vdW attraction. Instead, the spatulae tipped setae act as a nano-brush to detach the NPs from the wall or ceiling and allow QED induced EM radiation to produce the VUV radiation that provides the electrostatic attractive F_{ES} force to hold the gecko to the wall.

3.1 Mechanism of Setal Attachment

There is no need for a small preload normal force followed by a small backward drag for activating the gecko setae to produce shear force of 200 μN. Electrostatic force is prompt upon QED induced VUV radiation from NPs.

Gecko feet are not enormously overbuilt. Calculations that show 6.5 million setae on a 50g gecko having the 1300 N capacity to support a 133 kg mass only show nature never intended for the setae to hold the gecko to walls or ceilings. Moreover, it is not necessary for all setae to achieve the unlikely task of simultaneous orientation to the wall or ceiling to support the gecko.

On surfaces having the same roughness as the 200 nm scale of the spatulae, gecko adhesion is not reduced as nature may never have intended for the setae and spatulae to carry gecko weight. Instead, setae function appears to be brushing NPs off walls or surfaces.

3.2 Mechanism of Setal Detachment

Geckos manage to detach their feet rapidly in about 15 ms. It is not necessary for the angle between the setae and the wall or surface be increased for detachment because the electrostatic force ceases once the gecko stops moving his body or toes.

3.3 Integration

How the gecko integrates the attachment and detachment of millions of seta in stepping on and off a surface is not a problem for the electrostatic force. Attachment is activated spontaneously by the electric field F upon detaching millions of NPs from the wall or ceiling while inactivation proceeds by the gecko momentarily not moving the toes.

Electrostatic attraction provides the preload that in combination with friction allows the gecko to climb walls. Indeed, the electrostatic interaction between the toe and the surface induces a balanced internal force pair, and therefore external ground reaction during attachment and detachment would not be obvious and consistent with that observed..

3.4 Water Films and Capillary

If capillary adhesion occurs, thin films of water would have to present between the gecko toes and the walls or ceilings. The extent that a thin film of water forms over the gecko toe area depends on the relative humidity. Since geckos are found in tropical rain forests and dry rocky deserts, humidity obviously does not influence capillary adhesion.

With electrostatic attraction, thin films of water from atmospheric humidity is not expected to alter the gecko's walking ability, but NP detachment requires the surfaces to be near-dry. However, NP detachment is meaningless for surfaces under water and consistent with the fact [19] that geckos cannot walk under water.

3.5 Teflon® Surfaces

For the vdW force as the gecko attachment mechanism, the gecko's toe-hair is comprised of β-keratin. Geckos are claimed [3] to not walk on Teflon® surfaces because of polarizability.

Unlike the close proximity in the tribo-series [15] of electropositive glass and hair, Teflon® is strongly electronegative far removed from neutrality. Therefore, the electrostatic attraction of the gecko to Teflon® should be higher than to glass. From Sect. IIG, taking $p_1 = 7$ and $p_2 = -10$ gives $q_1 * q_2 = -289$. The attraction of the gecko to Teflon® should therefore be far greater than to glass.

However, observations [3] show geckos cannot walk on Teflon®. Given the strong electrostatic attraction of hair, the only conclusion that can be reached is that Teflon® having the lowest coefficient of friction of common materials is the reason the gecko cannot walk on Teflon®.

3.6 Self Adhesion

Paradoxically, gecko setae that readily attach to walls and ceilings [6] do not stick to each other. Indeed, pushing setae surfaces together does cause them to stick. Certainly, the vdW attraction should provide an adhesion under such conditions, but the contrary finding suggests the vdW attraction cannot be the mechanism by which the gecko walks.

Electrostatic attraction depends on the number and detachment of NPs by the toe-hairs. To show electrostatic and not vdW attraction controls gecko adhesion, lateral load tests should be conducted by adding a controlled quantity of say, 100 nm gold NPs to the gecko toe-hairs.

3.7 Self-Cleaning

Geckos captured in nature [6] have clean feet suggesting the setae and spatulae are self-cleaning. But why this is so is not known.

Electrostatic attraction from NPs in the toe-hairs and walls or ceilings is self-cleaning. But NPs are submicron and would not be visually observed. In contrast, MPs with diameters of 2.5 microns introduced to the gecko's foot-hairs are known [3, 6] to be rejected and found attracted to the surface.

If the removal of 2.5 micron MPs to the surface is construed as an act of self-cleaning, then the electric field F from NP charging induced by QED may find utility to charge and remove MPs in the manner of an electrostatic precipitator. The MPs alone can only produce IR and not VUV necessary to produce the field F. Indeed, the nano-brush may need to be seeded with NPs to produce the field F that charges the MPs.

3.8 Overbuilt for Adhesion

The observation [3] that gecko's setae are vastly overbuilt for adhesion to smooth ideal surfaces presupposes that nature intended the setae to carry the gecko weight while walking on walls and ceilings. If nature had another function in mind for the setae, say:

The millions of setae with spatulae tips act as a nano-brush to detach NPs from the surface.

If so, the gecko setae may not be overbuilt. That nature would have selected the setae as a nano-brush follows because to detach NPs is far less demanding task than supporting gecko weight by vdW attractions.

3.9 Gecko Carbon Nanotubes

The ability of geckos to climb walls and ceilings has led to research on how to simulate the gecko foot-hairs [3] based on adhesion by vdW force.

One such application [20] is fabricating carbon multiwalled nanotubes (MWNT) constructed on silicon substrates. The MWNT simulate the gecko setae having a length of about 65 microns and 10-20 nm in diameter. Of interest to NP charging is that most of the MWNT are aligned vertically, but in the solvent drying process entangled bundles were generally formed about 50 nm in diameter.

Compared to the gecko setae, the adhesive MWNT adhesive force is about 200 times higher suggesting the nature has been upstaged. However, this is not unexpected in NP charging provided a large number of NPs are included in the MWNT assembly. But the number of 50 nm entangled bundles is not given from which an assessment of NP charging by MWNT's may be made.

A way of testing the NP charging mechanism suggested in this paper is to simply dope the MWNT assembly with 100 nm silicon NPs.

4. CONCLUSIONS

Geckos walk on walls and ceilings by electrostatic attraction caused by charges produced from VUV radiation as toe-hairs detach NPs from walls and ceilings.

Gecko toe-hairs do not provide a load carrying function. Instead, nature appears to have given the toe-hairs the task of acting as a nano-brush to detach NPs while the gecko is walking.

Geckos are unlikely to walk on walls and ceilings by vdW attraction because contact over the nanoscale is not possible over the full area of the toe pads.

REFERENCES

[1] O. Cartier: Studien über den feineren Bau der Epidermis bei den Reptilien. II. Abt. Über die Wachsthumserscheinungen der Oberhaut von Schlangen und Eidechsen bei der Häutung, Arb. zool.-zoot. Inst. Würz, Vol. 1, pp. 239-258, 1874.

[2] H. R. Schmidt: Zur Anatomie und Physiologie der Geckopfote, Jena Z. Nature, Vol. 39, pp. 551, 1904.

[3] K. Autumn, A.M. Peattie: Mechanisms of Adhesion in Geckos, Integrative and Comparative Biology, Vol. 42, pp. 1081-1090 2002.

[4] C. Majidi: *Mechanics of Gecko Adhesion*, PhD. Thesis, University of California, Berkeley, Dept of Elect. Engr. and Comp. Sci., May 11, 2004.

[5] W.R. Hansen, K. Autumn: Evidence for self-cleaning in gecko setae, Proc. Nat. Acad. Scie. USA, 102, pp. 385-389, 2005.

[6] K. Autumn: How Gecko Toes Stick, Amer. Sci., 94, pp. 124-133, 2006.

[7] K.Y. Cho, I.S. Choi: Fabrication of Hairy Polymeric Films Inspired by Geckos: Wetting and Adhesion Properties, Adv. Funct. Mater., 18, pp. 1089-1096, 2008.

[8] L.D. Landau, E.M. Lifshitz: *Electrodynamics of Continuous Media*, Oxford, pp. 368-376, 1960.

[9] W.D. Dellit: Zur anatomie und physiologie der Geckozehe, Jena. Z. Nature, Vol. 68, pp. 613-656, 1934.

[10] K. Asano, S. Aonuma, F. Hatakeyama: Fundamental Study of an Electrostatic Chuck for Silicon Wafer Handling, IEEE Trans. Ind. Appl., Vol. 38, 2002.

[11] J. Berenqueres, M. Urago, S. Saito, K. Tadakuma, H. Meguro: Gecko inspired Electrostatic Chuck, IEEE Int. Conf. on Robotics and Biomimetics, pp.1018-1023, 2006.

[12] J. Berenqueres: You-Tube Video Presentation, 2006, www.youtube.com/watch?v=5_yFpOh7-Hg

[13] T. Prevenslik: A Unified Theory of Natural Electrification, in: *Proc. of 6th Int. Conf. App. Electrostatics*, 3-7.11.2008 Shanghai Maritime University, pp. 60-63.

[14] T. Prevenslik: QED Induced EM Radiation, See http://www.nanoqed.net/ 2008.

[15] A.F. Diaz, R.M. Felix-Navarro: A semi-quantitative tribo-electric series for polymeric materials: the influence of chemical structure and properties, J. Electro., pp. 277-290, 2004.

[16] R.W. Christy, A. Pytte: *The Structure of Matter: Introduction to Modern Physics*, Benjamin, New York, 1965.

[17] T. Prevenslik: Heat Transfer in Thin Films, in: *Third Inter. Conf. on Quantum Nano, Micro Tech.*, 1-6.2.2009 Cancun, Mexico.

[18] A.A. Guzhov, Y.A. Shuba: The Photoemission of Some Massive Insulators in the Vacuum Ultraviolet, Optical Technology, 38, pp. 198-199, 1971.

[19] H. Lee, B.P. Lee, P.B. Messersmith: A reversible wet/dry adhesive inspired by mussels and geckos, Nature, 448, pp. 338-341, 2007.

[20] B. Yurdumakan, R.B. Raravhiket, P.M. Ajayan, A. Dhinojwla: Synthetic gecko foot-hairs from multiwalled carbon nanotubes, Chem. Comm., pp.1081-1090, 2005.