Survey of Sticking Effects for Micro Parts Handling *

Ronald S. Fearing
Department of EE&CS
University of California
Berkeley, CA 94720-1770

Abstract

When parts to be handled are less than one millimeter in size, adhesive forces between gripper and object can be significant compared to gravitational forces. These adhesive forces arise primarily from surface tension, Van der Waals, and electrostatic attractions and can be a fundamental limitation to part handling in a gas environment. While it is possible to fabricate miniature versions of conventional robot grippers, for example from polysilicon, it appears that it will be difficult to overcome adhesion effects for the smallest parts. Thus, manipulation of parts on the order of 10 micron or smaller may best be done in a fluid medium using techniques such as laser trapping, or dielectrophoresis.

1 Adhesion Forces

A typical robotic manipulation scenario is the sequence of operations pick, transport, and place. For parts with masses of several grams, the gravitational force will usually dominate adhesive forces, and parts will drop when the gripper opens. For parts with size less than a millimeter (masses less than $10^{-6} Kg$), the gravitational and inertial forces may become insignificant compared to adhesive forces, which are generally proportional to surface area. When parts become very small, adhesive forces can prevent release of the part from the gripper. For example, a laser diode for an optical disk may be only $300\mu m$ in size [Hara et al 1993]. Figure 1 illustrates some of the effects which can be seen when attempting to manipulate micro parts. As the gripper approaches the part, electrostatic attraction may cause the part to jump off the surface into the gripper, with an orientation dependent on initial charge distributions. When the part is placed to a desired location, it may adhere better to the gripper than the substrate, preventing accurate placement.

*This work was funded in part by: NSF-PYI grant IRI-9157051.

Adhesion forces could be due to electrostatic, van der Waals or surface tension. Electrostatic forces arise from charge generation (triboelectrification) or charge transfer during contact. Van der Waals forces are due to instantaneous polarization of atoms and molecules due to quantum mechanical effects [Israelachvili, 1974]. Surface tension effects arise from interactions of layers of adsorbed moisture on the two surfaces. The goal of this paper is to survey causes of adhesion, provide estimates on the magnitude of their effect, and to survey methods for reducing the effect of adhesive forces.

For a simple numerical example to get an idea of the scale of the adhesion forces, consider the force between a spherical object and a plane (such as one finger of the gripper in Figure 2). The approximate force between a charged sphere and a conducting plane is given by:

$$F_{elec} = \frac{q^2}{4\pi\epsilon(2r)^2} , \qquad (1)$$

where q is charge, ϵ is the permittivity of the dielectric, and r is object radius. The assumed charge density is approximately $1.6 \times 10^{-6} Cm^{-2}$. It is interesting to note that the contact of good insulators such as smooth silica and mica can result in charge density up to $10^{-2} Cm^{-2}$ with pressures on the order of $10^6 Pa$ at $1\mu m$ distance [Horn and Smith 1992].

The van der Waals force for a sphere and plane is given approximately by [Bowling, 1988] as:

$$F_{vdw} = \frac{hr}{8\pi z^2}, \qquad (2)$$

where h is the Lifshitz-van der Waals constant, and z is the atomic separation between the surfaces. Of course, this formula is assuming atomically smooth surfaces; severe corrections need to be made for rough surfaces as the van der Waals forces fall off very rapidly with distance. For a rough estimate, we will assume a true area of contact of 1% of apparent area, or estimated force 1% of maximum predicted with smooth surfaces.

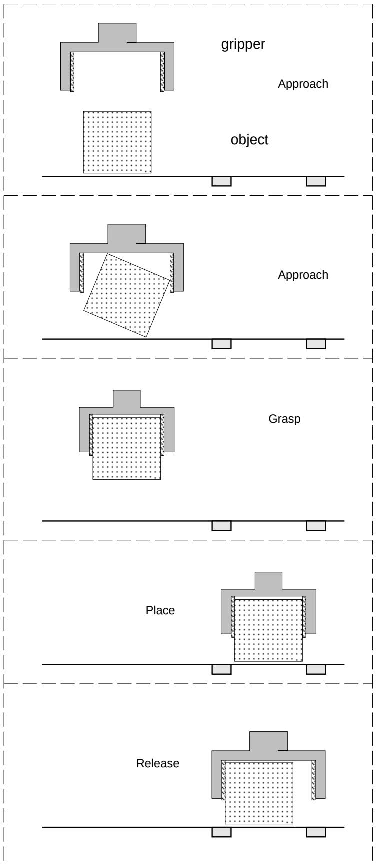

Figure 1: Pick-move-place operation with micro-parts. Due to sticking effects, parts may be attracted to the gripper during the approach and release phase, causing inaccurate placement.

In a high humidity environment, or with hydrophilic surfaces, there may be a liquid film between the spherical object and planar surface contributing a

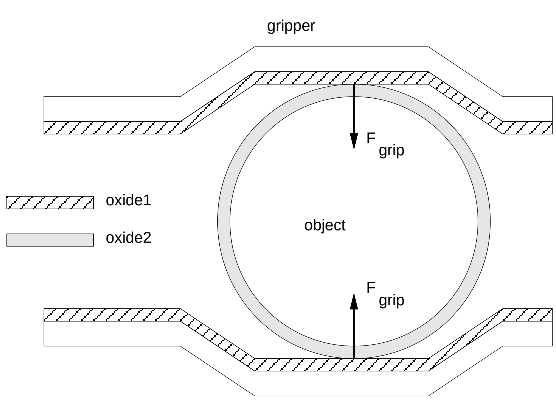

Figure 2: Micro-gripper holding spherical object.

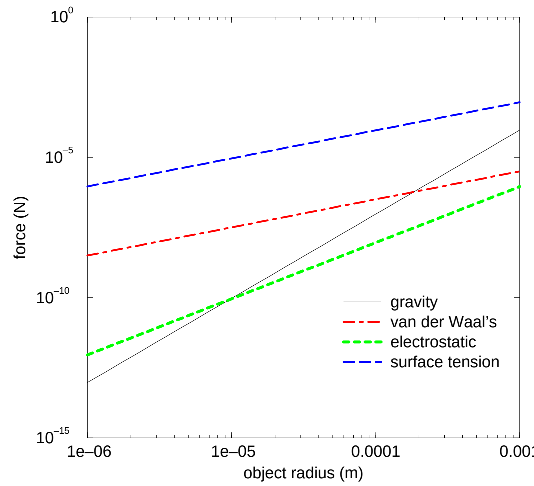

Figure 3: Gravitational, electric, van der Waals, and surface tension forces. Attractive force between sphere and plane.

large capillary force [Alley et al 1992]:

$$F_{tens} = \frac{\gamma(cos\theta_1 + cos\theta_2)A}{d}, \quad (3)$$

where γ is the surface tension ($73mNm^{-1}$ for water), A is the shared area, d is the gap between surfaces, and θ_1, θ_2 are the contact angles between the liquid and the surfaces. Assuming hydrophilic surfaces and a separation distance much smaller than the object radius [Bowling, 1988; Torii et al 1994]:

$$F_{tens} = 4\pi r\gamma, \quad (4)$$

where r is the object radius.

For a spherical part of silicon the gravitational force is:

$$F_{grav} = \frac{4}{3}\pi r^3 \rho_{Si} g, \quad (5)$$

where $\rho_{Si} = 2300Kgm^{-3}$ is the density of silicon. Figure 3 shows the comparison of forces. For accurate placement, adhesion forces should be an order of magnitude less than gravitational forces. Capillary forces dominate and must be prevented to allow accurate placement. Van der waals forces can start to be significant (with smooth surfaces) at about 100 μm radius, and generated electric charges from contacts could prevent dry manipulation of parts less than 10 μm in size.

While Figure 3 shows electrostatic to be the least significant force except for gravity, it can be argued that it is actually the most significant force for grasping and manipulation of $10\mu m$ to $1mm$ parts. First, the van der Waals force is only significant for gaps less than about $100nm$ [Scheeper et al 1992, Israelachvili, 1974]. Unless objects are very smooth, the effective distance between the object and the gripper will be large except at a few points of contact. Second, actual contact with a fluid layer needs to be made for surface tension to be significant, and a dry or vacuum environment could be used to eliminate surface tension effects. Finally, the electrostatic forces can be active over ranges of the order of the object radius. Surface roughness is much less important for electrostatic forces than for van der Waals.

1.1 Literature on Adhesion

The adhesion of particles to substrates has received substantial study for problems such as particulate contamination in semiconductor manufacturing [Bowling 1988; Hecht, 1990; Krupp, 1967; Zimon, 1969]. The recent developments in micro-electro mechanical systems (MEMS) and disk drives have stimulated the study of friction effects at the micro-scale. The normal coulomb friction effects seen at the macro-scale are quite different at the micro-scale, with large adhesive components. Several studies have examined surfaces using the atomic force micro scope [Torii et al 1994; Kaneko 1991]. A common problem in MEMS devices is that free standing micro-structures tend to stick to the substrate after being released during processing. The dominant mechanisms for sticking in these devices (which are typically constructed as a cantilever plate suspended 1 or 2 μm above the substrate) appears to be surface tension pulling the plate down, followed by van der Waals bonding. Recent papers have studied this problem [Ando et al 1991] and proposed solution methods of making the surfaces rough and hydrophobic [Legtenberg et al 1994; Alley et al 1991; Alley et al 1992; Scheeper et al 1992].

2 Adhesion due to Electrostatic Forces

Ensuring that parts and grippers are electrically neutral is difficult [Harper 1967]. Significant amounts of charge may be generated by friction forces and differences in contact potentials. While grounded conductors will drain off charge, insulators can maintain very high surface charge distributions. The local field intensity near a surface charge distribution can be estimated using Gauss's Law and Figure 4. Neglecting any interior field, the boundary conditions give

$$\hat{z} \cdot \epsilon_o \vec{E}(z=0) \;=\; \sigma_s, \qquad (6)$$

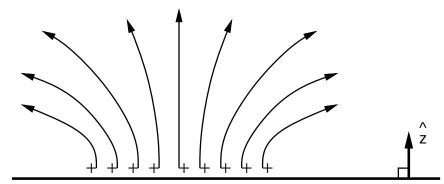

Figure 4: Field approximation near surface charge distribution.

where $\vec{E}$ is the electric field, $\hat{z}$ is the surface normal, and σ_s is the surface charge density Cm^{-2}. The near field approximation for a surface charge is then:

$$\vec{E} \approx \frac{\sigma_s}{\epsilon_o}\hat{z} \; . \qquad (7)$$

The force per unit area for parallel plates is

$$P \;=\; \frac{1}{2}\epsilon_o |E|^2 \;=\; \frac{\sigma_s^2}{2\epsilon_o} \; , \qquad (8)$$

where P is the pressure in Pascals.

At atmospheric pressure and centimeter size gaps, the breakdown strength of air (about $3 \times 10^6 Vm^{-1}$ [Lowell and Rose-Innes 1980]) limits the maximum charge density to about $3 \times 10^{-5} Cm^{-2}$, or peak pressures of about 50 Pa. Let l be the length of a side of a cube of silicon. Then the smallest cube which will not stick due to electrostatic force is:

$$l \;=\; \frac{\sigma_s^2}{2\epsilon_o \rho_{Si} g} \; , \qquad (9)$$

or about $2mm$ minimum size. Of course, a uniform charge distribution over such a large area is unlikely, although there could be local concentrations of charge of such magnitude. However, at very small gaps of the order of $1\mu m$ (less than the mean free path of an electron in air), fields two orders of magnitude higher have been observed [Horn and Smith 1992].

2.1 Contact Electrification

When two materials with different contact potentials are brought in contact, charge flows between them to equalize this potential. For metal-metal contact [Lowell and Rose-Innes, 1980; Krupp, 1967], a rough approximation to the surface charge density is:

$$\sigma_s \;=\; \frac{\epsilon_o U}{z_o} \qquad (10)$$

where U is the contact potential difference, which is typically less than 0.5 V, and z_o is the gap for tunneling, about 1 nm. Consider two metal spheres (insulated from their surroundings) brought into contact, then slowly separated. With a contact potential of 0.5

Materials in contact	charge density mCm^{-2}	electrostatic pressure Nm^{-2}	condition	ref.
$SiO_2 - Al$	2.0	2×10^5	1mPa N_2 80 nm SiO_2	[Lowell 1990]
soda glass - Al	0.13	10^3		
SiO_2-mica	5-20	1.4×10^6 to 20×10^6	N_2 at STP "atomically smooth"	[Horn&Smith, 92]
epoxy-Cu	0.04	100	10^4 Pa air	[Kwetkus et al 91]
glass-Au	4.2	10^6	air 40-60% RH	[Harper 67]
nylon-steel	.0036	1		
polystyrene	.0002	2×10^{-6}		

Table 1: Charge from contact electrification. Pressure is the effective pressure due to the generated charge.

V, the initial charge density according to eq.(10) will be about $4mCm^{-2}$, with field strength $5 \times 10^8 Vm^{-1}$. For small gaps (order 1 nm), electron tunneling and field emission [Lowell and Rose-Innes, 1980] will transfer charge, and then for larger gaps (order $1 \mu m$) air breakdown can occur. In laboratory experiments, contact electrification has been shown to generate significant charge density, which could cause adhesion (see Table 1).

2.2 Charge storage in dielectrics

In principle, using conductive grippers can reduce static charging effects. However, the objects to be handled, such as silicon parts, can be covered with good insulator layers, such as native oxides. Up to 1 nm of native oxide is possible after several days in air at room temperature Morita et al [1990]. This native oxide is a very good insulator, and can withstand a maximum field strength of up to $3 \times 10^9 Vm^{-1}$ [Sze 1981]. This implies that significant amounts of charge can be stored in the oxide. With the permittivity of silicon $\epsilon = 3.9\epsilon_o$, peak pressures according to eq.(8) are on the order of $10^8 Pa$. With a contact area of only $10 (nm)^2$, this would be a force of 10 nN, enough to support a 30 μm cube against gravity.

Consider an initially charged object grasped as shown in Figure 2, by a grounded gripper. In regions where the two dielectrics are not in contact, charge will be induced on the opposite surface. As suggested in Figure 5, local regions of charge can remain in the dielectric layer in spite of "intimate" contact between two nominal conductors. The surface roughness can prevent charge neutralization through intimate contact of oppositely charged regions. The residual charge can cause adhesion.

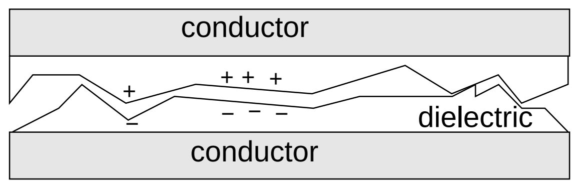

Figure 5: Physical model of contact with charge in oxide layer.

It can be very difficult to remove stored charge in a dielectric layer. Consider a simplistic model for the electrical contact, with one capacitor representing the air gap and a second capacitor in series representing the dielectric layer as shown in Figure 6. It is apparent that shorting the terminals will not instantaneously remove charge from both capacitors, hence there will be a residual attraction force between the gripper and the object. The stored charge (and hence electric field) decays as a first order exponential, with time constant:

$$\tau = \rho(\epsilon + \epsilon_o \frac{d_1}{d_2}) \qquad (11)$$

where ρ is the resistivity of the dielectric. For SiO_2 with resistivity $\rho = 10^{12} \Omega m$, dielectric thickness 10 nm, and air gap 20 nm, the time constant τ is about 40 seconds, significantly reducing cycle time. Charge storage in dielectric layers may result in undesired adhesions in electrostatic grippers [Nakasuji and Shimuzu, 1992] and in electrostatic micro-actuators where contact is made with an insulating layer [Anderson and Colgate, 1991].

3 Conclusions

As we have seen, electrostatic, van der Waals, and surface tension forces can be significant compared to

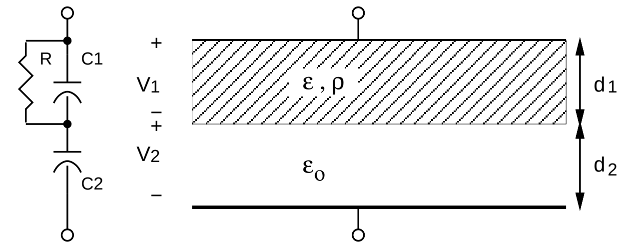

Figure 6: Equivalent circuit model of contact. ρ is the resisitivity of the dielectric.

the weight of small parts. Conventional assembly methods such as pick-move-place do not scale well for sub-millimeter parts. One possible attractive alternative is assembly while immersed in a fluid, which eliminates electrostatic and surface tension effects [Yeh and Smith 1994].

There are several design strategies which can be used to reduce adhesive effects in micro-grippers. Figure 7 compares finger tip shapes. Clearly, the spherical fingertip has reduced surface contact area and better adhesive properties, unlike the micro-gripper shown in Figure 8 which can be fabricated using planar surface micro-machining.

Proper choice of gripper materials and geometry can be used to reduce adhesion:

1. Minimize contact electrification by using materials with a small contact potential difference for the gripper and object.

2. Use conductive materials which don't easily form highly insulating native oxides

3. Gripper surfaces should be rough to minimize contact area.

4. The high contact pressure from van der Waals and electrostatic forces can cause local deformation at the contact site [Bowling 1988]. This deformation can increase the contact area and increase the net adhesive force. Hard materials are preferable to rubber or plastic.

5. A dry atmosphere can help to reduce surface tension effects. Surface tension can be used to help parts adhere better to the target location than the gripper.

As discrete parts are designed continually smaller to make equipment smaller, more economical and higher performance, there will be a greater need for understanding how to manipulate and assemble micro-parts. Because of adhesive forces, grasping and particularly ungrasping of these parts can be complicated. Good

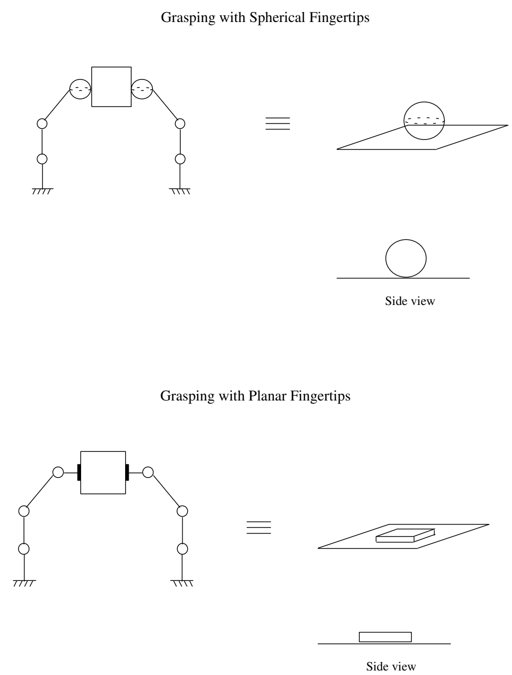

Figure 7: Comparison of finger types for grasping. A spherical fingertip will minimize electrostatic and surface tension forces, and can be roughened to minimize van der Waals forces.

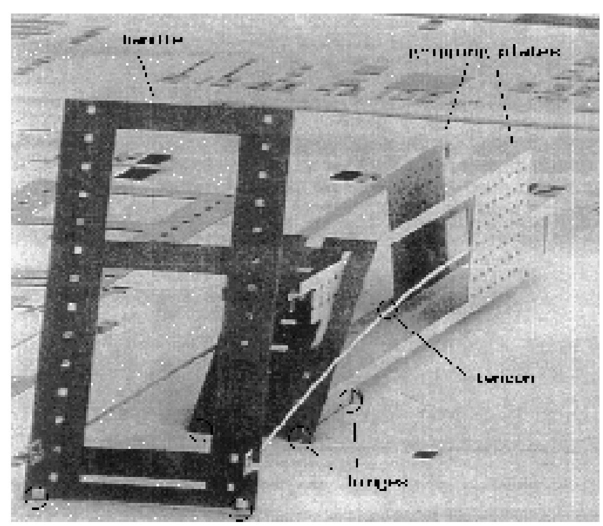

Figure 8: Micro-gripper mechanism using polysilicon hinge technology [Pister et al 1992]. The gripper is about $200\mu m$ high and is externally actuated by tendon drive.

models of surfaces and the physics of contact will be needed to implement reliable manipulation and assembly systems.

Acknowledgments

I would like to thank Mr. Hiroaki Furuichi for helpful discussions and providing access to informative papers.

References

[1] R.L. Alley, G.J. Cuan, R.T. Howe, K. Komvopoulos, "The effect of release-etch processing on surface microstructure stiction." *IEEE Solid-State Sensor and Actuator Workshop* pp. 202-207, Hilton Head Island, SC, USA, 22-25 June 1992.

[2] R.L. Alley, P. Mai, K. Komvopoulos and R.T. Howe, "Surface roughness modification of interfacial contacts in polysilicon" *7th Int. Conf. on Solid State Sensors and Actuators (Transducers '91)*, pp. 288-291, San Francisco, June 1994.

[3] K. M. Anderson and J. Edward Colgate, "A model of the attachment/detachment cycle of electrostatic micro actuators", *ASME Micromechanical Sensors, Actuators, and Systems*, DSC-vol. 32, pp. 255-268, Atlanta, GA Dec. 1-6, 1991.

[4] Y. Ando, H. Ogawa, Y. Ishikawa, "Estimation of attractive force between approached surfaces", *Second Int. Symp. on Micro Machine and Human Science*, pp. 133-138, Oct. 8-9, 1991, Nagoya, Japan.

[5] R.A. Bowling, "A theoretical review of particle adhesion", in *Particles on Surfaces 1: Detection, Adhesion and Removal*, ed. K.L. Mittal, pp. 129-155, New York: Plenum Press 1988.

[6] S. Cunningham, "Measurement of the dynamics of multiple contact electrification of polymers by metals." IN: *Electrostatics 1991*. Eighth International Conference, Oxford, UK, 10-12 April 1991). Edited by: O'Neill, B.C. Bristol, UK: IOP, 1991. p. 205-10.

[7] T. Fukuda, M. Fujiyoshi, K. Kosuge, and F. Arai, "Electrostatic micromanipulator with 6 DOF" *IROS '91. IEEE/RSJ International Workshop on Intelligent Robots and Systems*, Osaka, Japan, Oct. 1991.

[8] S. Hara, H. Nakada, R. Sawada, and Y. Isomura, "High Precision Bonding of Semiconductor Laser Diodes", *Int. J. Japan Soc. Prec. Eng.*, vol. 27, no. 1, pp. 49-53, March 1993.

[9] W.R. Harper, *Contact and frictional electrification*, Oxford: Clarendon Press, 1967.

[10] D.A. Hays, "Electrostatic adhesion of non-uniformly charged dielectric spheres", *Int. Phys. Conf. Series No. 118: section 4, Electrostatics '91*, pp. 223-228, 1991.

[11] L. Hecht, "An introductory review of particle adhesion to solid surfaces." *Journal of the IES*, 1990 Mar-Apr, v33 n2:33-37.

[12] R.G. Horn, D.T. Smith, "Contact electrification and adhesion between dissimilar materials." *Science*, 17 April 1992, vol.256, (no.5055):362-4.

[13] J.N. Israelachvili, "The nature of van der Waals forces", *Contemp. Physics*, vol. 15, no. 2, pp. 159-177.

[14] R. Kaneko, "Microtribology related to MEMS" *IEEE Micro Electro Mechanical Systems* pp. 1-8, Nara, Japan Jan. 30 - Feb. 2 1991.

[15] C-J. Kim, A.P. Pisano, and R.S. Muller, "Silicon-processed overhanging microgripper", *Jnl. of Microelectromechanical Systems*, pp. 31-36, vol. 1, no. 1, March 1992.

[16] H. Krupp, "Particle adhesion theory and experiment", *Advances in Colloid and Interface Science* , vol. 1, pp. 111-239, 1967.

[17] B.A. Kwetkus, B. Gellert, and K. Sattler, "Discharge phenomena in contact electrification" *Int. Phys. Conf. Series No. 118: section 4, Electrostatics '91*, pp. 229-234, 1991.

[18] R. Legtenberg, H.A.C. Tilmans, J. Elders and M. Elenspoek, "Stiction of surface micromachined structures after rinsing and drying: model and investigation of adhesion mechanisms", *Sensors and Actuators*,vol. 43, pp. 230-238, 1994.

[19] J. Lowell, "Contact electrification of silica and soda glass", *J. Phys. D: Appl. Phys.* vol. 23, pp. 1082-1091.

[20] J. Lowell and A.C. Rose-Innes, "Contact electrification", *Advances in Physics*, vol. 29, no. 6, pp. 947-1023, 1980.

[21] M. Morita, T. Ohmi, E. Hasegawa, M. Kawakami, and M. Ohwada, "Growth of native oxide on a silicon surface", *J. Appl. Physics*, vol. 68, no. 3, pp. 1272-1281, 1990.

[22] M. Nakasuji and, H. Shimizu, "Low voltage and high speed operating electrostatic wafer chuck." *Journal of Vacuum Science & Technology A (Vacuum, Surfaces, and Films)*, Nov.-Dec. 1992, vol.10, (no.6):3573-8.

[23] K. Naito, T. Kondo, and S. Matsuki, "[Watch assembly line by computer control]." *Journal of the Japan Society of Precision Engineering*, Sept. 1976, vol.42, (no.9):881-7.

[24] K.S.J. Pister, M.W. Judy, S.R. Burgett, and R.S. Fearing, "Microfabricated Hinges", *Sensors and Actuators A* , vol. 33, pp. 249-256, 1992.

[25] D.S. Rimai, L.P. DeMejo,; R.C. Bowen, "Adhesion-induced deformations of polymeric substrates: particle size dependence of the contact area." *Journal of Applied Physics*, 15 Oct. 1989, vol.66, (no.8):3574-8.

[26] H. Saeki, T. Tanaka, T. Fukuda, K. Kudou, et al "New electrostatic micromanipulator which dislodges adhered dust particles in vacuum". *Journal of Vacuum Science & Technology B (Microelectronics Processing and Phenomena)*, Nov.-Dec. 1992, vol.10, (no.6):2491-2.

[27] P.R. Scheeper, J.A. Voorthuyzen, W. Olthius and P. Bergveld, "Investigation of attractive forces between PECVD silicon nitride microstructures and an oxidized silicon substrate" *Sensors and Actuators A (Physical)*,vol.A30 pp.231-239, 1992.

[28] M. Suzuki, S. Watanabe, N. Yoshimura, and H. Fujita, "Frictional properties of various thin films for micromechatronics", *Second Int. Symp. on Micro Machine and Human Science*, pp. 189-195, Oct. 8-9, 1991, Nagoya, Japan.

[29] S.M. Sze, *Physics of Semiconductor Devices*, 2nd ed. New York: Wiley, 1981.

[30] A. Torii, M. Sasaki, K. Hane, and S. Okuma, "Adhesive force distribution on microstructures investigated by an atomic force microscope.", *Sensors and Actuators A (Physical)*,Aug. 1994, vol.A44, (no.2):153-8.

[31] A.E. Uber III, J.F. Hoburg, G.W. Penney, "Experimental investigation of electrostatic effects in the adhesion of dry dusts." *IEEE Transactions on Industry Applications*, Jan.-Feb. 1984, vol.IA-20, (no.1):148-54.

[32] Y. Yamazaki, "Current situation of the automatic assembly in wrist watch industry". *Journal of the Japan Society of Precision Engineering*, Feb. 1991, vol.57, (no.2):224-7.

[33] H. Yeh, J.S. Smith, "Fluidic self-assembly for the integration of GaAs light-emitting diodes on Si substrates." *IEEE Photonics Technology Letters*, vol.6, (no.6):706-8, June 1994.

[34] A.D. Zimon, *Adhesion of dust and powder*, New York: Plenum Press, 1969.