Chapter 5

Electrostatic interaction between tip and sample

The discovery of silicon based transistor in 1948 led to the development of micrometer scale devices, making it possible to produce complex computational system that require a fraction of space needed by devices produced from older vacuum-tube technology. However, a self assembly of molecules on metal, semiconducting [1–4] or insulating surfaces provided new possibilities for practical solution in the construction of nanoscale devices. Using self-assembly processes to make nanoscale devices eliminate the need for complex machinery required to manipulate objects with nanometer resolution. Additional research has also shown there are possible uses of nanowires as inter-connects for interfacing nanoscale devices to microelectronic systems. An understanding of theses nanosystems is still required the development of working devices. As development continues in the field of cytotechnology, a need has arisen for the characterization of these nanoscale systems. Not only is electronic characterization necessary, but understanding of the interacting forces acting on these systems is also necessary. Knowledge of electrostatic interaction present in a nanosystem can provide a powerful insight into the mechanism controlling the electronic properties [5]. For example, in case
of molecular self assembly, measuring the electrostatic potential of the monolayer can provide important information on the properties of molecular charge distribution. Interpreting these distribution of the charges is useful for understanding the mechanism behind molecular conduction and molecule’s adsorption on a surface. Since molecules and other nanostructures have the dimensions of the order of nanometers, a high lateral resolution is required to probe the electrostatic field near these objects. Electrostatic interaction is one of the most important forces that controls the electronic properties of the nanostructures. In order to evaluate devices formed with single molecules, nanoparticles, nanorods and other single nanocomponents on insulating surfaces, there is a need to understand the electrostatic force between probe and the insulating surface.

5.1 Introduction

Knowledge of electric fields in the typical tip-sample configuration is essential for operating the scanning tunneling microscope, the atomic force microscope (AFM), the Electrostatic Force Microscope (EFM), and the other related probe microscopes. Knowledge of the tip structure on the macroscopic scale is required for calculation of the van der Waals interaction between the tip and surface. Understanding the electrostatic force of attraction of insulating surface is of importance in many different fields including atomic force microscopy, semiconductor contamination, and particle adhesion to pharmaceutical drugs. However, for metals in contact with non-metals, high densities of charge on the non-metal surface may give rise to attractive electrostatic forces. In EFM, the images are strongly dependent on the shape and size of the tip. Several expressions for the electrostatic force between the conducting tip and sample based on various geometric models resembling tip-sample shape are proposed [6]. The problem of getting an analytical expression for the force between conducting tip and insulating sample becomes challenging because the tip-cantilever assembly has a complex geome-
try. The literature contains no theory of electrostatic attraction for the case of non-equilibrium excess charge residing on an insulating surface. Most of the theoretical and experimental studies on EFM have been focused on the force and capacitance between tip and a metallic sample [7]. Tip shape effects on electrostatic interactions with insulating samples have not been studied in detail.

In this chapter we discuss the various tip-sample geometries for the insulating sample. A formula for the electrostatic force between conducting spherical tip and the insulating surface in proximity is discussed which has been applied to an experimentally obtained results. Initial efforts were made on home-built AFM to study electrostatic interaction between tip and sample. However, a formula has been derived for the electrostatic force between the conducting tip and a metallic sample coated with a thin layer of polarizable dielectric of known dielectric constant by exploiting the fact that the tip-sample configuration in scanning probe microscopes can be represented as confocal hyperboloid surfaces of revolution in a prolate spheroidal coordinate system [8, 9]. It is compared with the configuration of parallel plate. The general behavior of the dependence of the force on tip-sample separation, and the thickness of the dielectric film has been verified experimentally using a conducting atomic force microscope. The results are in better agreement over a wide range of distances, as compared to the commonly used sphere-on-plane approximation.
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5.2.1 Theory

Consider two spheres 1 and 2 of radii \(a\) and \(b\) respectively as shown in Fig. 5.1. The distance between their centers is denoted by \(c\). With the concept of self- and mutual capacitances for two spheres [8], the coefficient \(c_{11}\) is the charge on sphere 1 and \(c_{12}\) that on sphere 2 when sphere 2 is grounded and sphere 1 is at unit potential. Consider sphere 1 is at unit potential having a charge \(q = 4\pi \epsilon a\) at its center \(O'\) and sphere 2 at zero potential having an image charge \(q' = -4\pi \epsilon ab/c = 4\pi \epsilon na\) at a distance \(b^2/c = nb\). Again restoring sphere 1 at unit potential with the image

\[
q'' = \frac{\pm aq'}{(c-nb)} = \frac{\pm 4\pi \epsilon n a}{1-n^2} \tag{5.0}
\]
at a distance $a^2/(c-nb) = ma/(1-n^2)$ to the right and then restore sphere 2 at zero potential by placing an image

$$q'' = \frac{-bq''}{c-ma/(a-n^2)} = \mp 4\pi\epsilon mn^2a \left(\frac{1}{1-m^2-n^2}\right)$$  \hspace{1cm} (5.0)

at the proper distance $O$, and so forth. Ultimately, adding up the charges on sphere 1 gives

$$C_{11} = 4\pi\epsilon a \left(1 + \frac{mn}{1-n^2} + \frac{m^2n^2}{(1-n^2)^2-m^2} + \ldots\right)$$  \hspace{1cm} (5.0)

Adding up charges on sphere 2 gives,

$$C_{12} = 4\pi\epsilon \left(-na - \frac{mn^2a}{1-n^2-m^2}\right)$$  \hspace{1cm} (5.0)

The force of attraction between the two spheres can be written as

$$F = \frac{1}{2} \left(\frac{\partial C_{11}}{\partial c^2} V_1^2 + \frac{\partial C_{12}}{\partial c} V_1 V_2 + \ldots\right)$$  \hspace{1cm} (5.0)

Since $V_2 = 0$, the above equation can be written as

$$F = \frac{V_1^2 \partial C_{11}}{2 \partial c}$$  \hspace{1cm} (5.0)

Considering a special case of some interest is that of a sphere and a plane. We can get this case by letting $c-d=b \to \infty$, where $d$ is the distance from the plane to the center of sphere 1. In this case, $n \to \infty$, $m \to 0$, and $m/|1-n|=a/d$ so that we have,

$$C_{11} = 4\pi\epsilon a \left(1 + \frac{a}{2d} + \frac{a^2}{4d^2-a^2} + \ldots\right) = 4\pi\epsilon a \sinh \alpha \sum_{n=1}^{\infty} cschn\alpha$$  \hspace{1cm} (5.0)

where, $d = \cosh \alpha$ [8, 9]. In this case, the force between sphere and plane can be written as

$$F = \frac{V_1^2 \partial C_{11}}{2 \partial d} = a^2V_1^2 \left(\frac{1}{2d^2} + \frac{8ad}{(4d^2-a^2)^2} + \ldots\right)$$

$$= 2\pi\epsilon V_1^2 \sum_{n=1}^{\infty} (cschn\alpha - ncothn\alpha)$$
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Considering this plane is an infinite dielectric of dielectric constant \( K \). In this case the capacitance can be written as

\[
C_{11} = 4\pi e a \sum_{n=1}^{\infty} \left( \frac{K - 1}{K + 1} \right)^{n-1} \text{csch} \alpha
\]  

(5.0)

and the force between conducting sphere and infinite dielectric is given by

\[
F = 2\pi e V^2 \sum_{n=1}^{\infty} \left( \frac{K - 1}{K + 1} \right)^{n-1} (\text{csch} \alpha - \text{coth} \alpha)
\]  

(5.0)

5.2.2 Experimental details

Experimental setup

Before doing the experiments on Burleigh head, the preliminary experiments were performed on homemade AFM to get the feel of force spectroscopy. The experimental apparatus used in this work consist of reduction lever type coarse approach mechanism, piezo electric scanner and lever based optical deflection system mounted on a table top vibration isolation system. The sample is mounted on the quadrant piezoelectric scanner while the cantilever was spring loaded on a macor machinable ceramic block [10].

In our AFM, the mechanical set up consists of AFM head along with acoustic and building vibration isolation. The AFM head comprises of a cantilever holder having spring action with a macor machinable ceramic mount, coarse and fine approach mechanism and translation stages for laser and detector (sensitivity: 10 mV per nm) assembly for good alignment of optical beam. Fig. 5.2 a sketch of showing different mechanical parts of the set-up. The coarse approach consists of screw ball bearing with a spring action arrangement for the adjustment in the range of 0.1 to 0.5 cm separation between tip and sample. A differential screw is used for fine motion in the range of 1 to 2.5 mm Mitu. The least count of the screw is 1000 Å. A lever demagnification of 10 makes the adjustment possible with nanometer precision. The sample is attached to the quadrant scanner piezo
Figure 5.2: Sketch showing various mechanical parts in the setup.

tube and the cantilever assembly is mounted on a driving piezo with the help of spring action cantilever holder for oscillating the cantilever for dynamic mode of operation. The piezo-drive assembly used for scanning and controlling the Z motion of the tip. The measured Z sensitivity is approximately 50 Å/V.

Cantilever

The stylus cantilevers were prepared from ~1 mm diameter copper wires flattened to dimensions a few millimeters long (5 mm). 0.35 mm W wires were chemically etched to form a tip (tip radius: ~50 nm). Fig. 5.3 shows the schematic of the tip preparation setup. The details of the etching process is given elsewhere [11]. The W tips were then attached to the copper strip to form the cantilever with known
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Figure 5.3: Schematic of hybrid cantilever of thickness: 38.9 µm, width: 1.2 mm, length: 5 mm.

Figure 5.4: Resonant frequency of the hybrid cantilever.

tip geometry. A minute mirror was attached to the back side of the cantilever to facilitate reflection of the laser beam without much reduction in the resonance frequency. The schematic of the hybrid cantilever is shown in Fig. 5.3. The dynamic in situ measurement yielded a resonance frequency of 1.3 KHz (Fig. 5.4). The force constant of the hybrid cantilever was calculated by $\omega^2 = k/m$ which is 107 N/m.

Before performing the electrostatic measurements, cantilever deflection versus displacement was recorded at zero bias to define a zero of the tip-sample separation as the sample position at which jump to contact occurs. Then the electrostatic measurements were performed to record force curves in attractive region at differ-
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Figure 5.5: Comparison of force on metal and dielectric.

ent bias. The bias was applied to the hybrid cantilever while keeping the sample at ground. Two types of samples were studied in this work. Pt coated Si was used as conductor and thin sheet of mica (thickness \( \sim 22 \, \mu m \)) was used as insulator. Mica was grounded by coating Pt on back side of the mica sheet neutralize the accumulated charges.

5.2.3 Results and discussion

Fig. 5.5 shows the comparison between the force on metal and dielectric for sphere-on-plane geometry, in which the force for dielectric is comparatively smaller than the force for metal. Fig. 5.6 (A) and (B) shows cantilever deflection versus distance curves taken in static mode, on the Pt coated Si and mica at different applied biases. The observed force for mica is comparatively smaller than the force observed of Pt coated Si.

The experiments were then repeated for mica, on modified Burleigh AFM (thickness \( \sim 22 \, \mu m \)) in NC-AFM using a stylus gold coated cantilever made up of heavily doped Si having resistivity of 0.01 \( \Omega cm \) (MikroMasch NSC36, force constant (k) =1.75 N/m, R = 500 \( \AA \) and resonant frequency (f) = 160 KHz).
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Figure 5.6: Force-distance curves taken on (A): Pt coated Si and (B): mica at different applied voltage.

Prior to the experiment, the silica gel was placed in AFM chamber near the tip-sample assembly to avoid the contribution from residual water layer. Before the experiments in non-contact mode, contact mode force curves were obtained to estimate the zero points of X and Y axes which are tip-sample distance and force respectively. These are the points at which the force on the cantilever becomes zero during the approach. Current limiting resistor was used in series with the tip-sample junction to avoid the excessive current flow due to physical contact of the tip with sample which may lead the modification of the tip/sample surface.

By monitoring the dc shift of the cantilever, static deflection of the cantilever as a function of distance is measured. In Fig. 5.7 the measured electrostatic forces versus tip-sample distance at different bias were plotted. The normalized curves in inset of fig. are overlapped suggesting $V^2$ dependency. The electrostatic forces are detected at separations larger than 100 nm, and is dominant for separations greater than few angstroms. Circular symbols in the curves represent experimental force obtained by the sharp tip with spherical geometry, while blue lines show the theoretical curves for sphere-on-plane approximation using Eq. 5.2.1. The data is fitted using Levenberg-Marquardt [12] method for $R = 53.6$ nm. From the Fig. 5.7 it can be seen that general behavior of force-distance curve is in reasonably good agreement with the geometry of sphere-on-plane for distances up to $\sim 500 \, \text{Å}$.
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Figure 5.7: (A): Comparison of experimental results obtained on mica, with Sphere plane approximation for different bias voltages (R=530 Å. (B): Force vs 1/s for different applied voltages.)

EFM especially of insulating surface allows spatially resolved analysis of the sample-probe electrostatic interaction due to the electric-charge distribution, and the dielectric response of the material. In this work, dielectric constant of mica was taken to be 7 [13]. Electrostatic force due to the tip-surface interaction depends critically on the tip/surface properties and experimental setup. On the macroscopic scale, tip and surface charging can dominate the interactions, and in some cases even prevent stable imaging. It is commonly assumed that the very large attractive forces which prevent stable imaging of some insulating oxides are due to significant surface charging. The charge-charge interaction for a neutral surface, where all the charged defects have been compensated without atomic displacement, decays exponentially into the vacuum and would introduce a contribution to the tip-surface force only at small tip-surface separations. Charge dipole and dipole-dipole interactions [14] have much longer range than charge-charge interactions, and can introduce very long-range electrostatic contributions to the tip-surface interactions.

A plot of normalized force versus 1/s is also obtained for different applied bias as shown in Fig. 5.7(B). A linear behavior between F Vs 1/s has been shown for
metallic sample. By measuring the slope $P = \pi \varepsilon_0 V^2 R_{eff}$ we can estimate the effective radius of the tip. But in case of dielectric sample the linear behavior is observed up to 150 nm while for smaller distances the absolute value is changing for each applied bias.

5.3 Force on a conducting tip near metallic surface coated with layer of polarizable dielectric: Theory and Experiment

5.3.1 Theory

A general formula for electrostatic potential for conducting tip-sample geometry was developed by Russell [15] by using a prolate spheroidal coordinate system and later used by several workers in connection with STM [16] and Scanning Field Emission Microscopy [17, 18]. Fig. 5.8 shows a general representation of prolate spheroidal coordinate system. An expression for the force between the conducting tip and a sample due to the presence of the potential difference as a function of tip-sample distance assuming the geometry of a confocal hyperboloid is obtained by S. Patil et.al. [19, 20] The prolate spheroidal coordinate system, which is particularly suitable, is given by

$$
x = a[(\xi^2 - 1)(1 - \eta^2)]^{\frac{3}{2}} \cos \phi, \quad y = a[(\xi^2 - 1)(1 - \eta^2)]^{\frac{3}{2}} \sin \phi, \quad z = a\xi\eta \quad (5.0)
$$

where $1 \leq \xi \leq \infty$, $-1 \leq \eta \leq 1$ and $0 \leq \phi \leq 2\pi$ describe the permissible ranges of the coordinates $\xi$, $\eta$ and $\phi$. The tip surface was assumed to be represented by a portion of hyperboloidal surface $\eta = \eta_{tip} = \sqrt{s/(s + R)}$ bounded by a maximum distance $r_{max}$ from the $z$ axis. Here, $s$ is the tip-sample distance and $R$ is the tip radius. The sample surface is characterized by $\eta = \eta_{sample} = 0$. In this work we extend these calculations for the estimation of force on the tip when the conducting planar
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Figure 5.8: General representation of prolate spheroidal coordinate system

A surface is coated with a thin layer of polarizable dielectric with a known dielectric constant on the side facing the tip. In addition, it is assumed that this surface can be approximated by a confocal hyperboloid surfaces of revolution tangent to the dielectric surface at the point D (see Fig. 5.9), the equipotential surfaces continue to be confocal hyperboloids and the electrostatic potential becomes only a function of $\eta$. The approximation of treating the plane free surface of the dielectric as a confocal hyperboloid is reasonably good if the thickness of the dielectric layer is small enough so that significant departure of the hyperboloid from the plane occurs at distance larger than $r_{\text{max}}$ when measured from D. Where $r_{\text{max}}$ is the radius at the intersection of bottom of the tip and the surface of the cantilever [19]. In the absence of this cutoff, the expression is logarithmically divergent.

Using the notation of Russell

$$a = \sqrt{s(s + R)}; \quad \eta_{\text{tip}} = \sqrt{\frac{s}{s + R}}; \quad \eta_{D} = \frac{t_{\text{oxide}}}{a} \quad (5.0)$$

where 'a' is the focus-sample distance, $t_{\text{oxide}}$ is the dielectric layer thickness at D. The parameters $\eta_{\text{tip}}$ and $\eta_{D}$ define surfaces of the tip and the approximating
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Figure 5.9: Schematic diagram of the tip-sample geometry used for the calculations

confocal hyperboloid. In ensuring discussion, the word 'sample' refers to the plane conducting surface which will be assumed to be at zero potential. The conducting tip will be at a potential \( V_b \). The Laplace equation reduces to a one dimensional ordinary differential equation whose general solution is of the form

\[
V(\eta) = A \ln \lambda + B
\]  

(5.0)

where

\[
\lambda = \frac{1 + \eta}{1 - \eta}
\]  

(5.0)

and A and B are arbitrary constants. However the region of interest has to be decided into two separate regions such that \( \eta_{tip} \geq \eta > \eta_D \) (region I) contains free space and \( \eta_D \geq \eta \geq 0 \) (region II) contains the dielectric of dielectric constant \( k \). The solution to the Laplace equation \( V_1(\eta) \) and \( V_2(\eta) \) in the region I and II respectively satisfying the following condition.

\[
V_1(\eta_{tip}) = V_b; \quad V_1(\eta_D) = V_2(\eta_D)
\]  

(5.0)
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and

\[ V_2(0) = 0; \quad V_1'(\eta_D) = kV_2'(\eta_D) \quad (5.0) \]

are found to be

\[ V_1(\eta) = V_b \left( \frac{k \ln \lambda - (k - 1) \ln \lambda_D}{k \ln \lambda_{tip} - (k - 1) \ln \lambda_D} \right) \quad \text{Region I} \quad (5.1) \]

\[ V_2(\eta) = V_b \left( \frac{\ln \lambda}{k \ln \lambda_{tip} - (k - 1) \ln \lambda_D} \right) \quad \text{Region II} \quad (5.2) \]

where

\[ \lambda_D = \frac{1 + \eta_D}{1 - \eta_D}; \quad \lambda_{tip} = \frac{1 + \eta_{tip}}{1 - \eta_{tip}} \quad (5.2) \]

For the purpose of calculating the force on the tip, only the electric field in a region I is needed. The electric field at a point \( P(\eta_{tip}, \xi) \) on the tip surface is given by

\[ \vec{E} = \beta_k \left( -2\alpha \frac{\hat{\eta}}{\sqrt{(\xi^2 - \eta_{tip}^2)(1 - \eta_{tip}^2)}} \right) \quad (5.2) \]

where

\[ \alpha = \frac{V_b}{\ln \lambda_{tip}} \quad (5.2) \]

and the factor in the bracket is the field at the tip in the absence of dielectric layer. The effect of the dielectric is buried in the factor \( \beta_k \) which is given by

\[ \beta_k = \frac{k \ln \lambda_{tip}}{k \ln \lambda_{tip} - (k - 1) \ln \lambda_D} \quad (5.2) \]

so that \( \beta_k \to 1 \) when either \( k \to 1 \) or \( \lambda_D \to 1 \) or both. Since the calculation of the force on the tip proceeds identically to that undertaken, the expression for this force when the dielectric layer is present is given by

\[ \tilde{F}_z = \beta_k^2 F_z \quad (5.2) \]

where \( F_z \) is the force for a conductor without dielectric layer [19], which is given by

\[ F_z = (4\pi\epsilon_0)V_b^2 \left( \frac{\ln(1 + r_{\text{max}}/R^2)(1 + \frac{R}{s})}{\ln^2(\frac{1 + \eta_{tip}}{1 - \eta_{tip}})} \right) \quad (5.2) \]
5.3 Force on a conducting tip near metallic surface coated with layer of polarizable dielectric: Theory and Experiment

Figure 5.10: A: Comparison of force on metal and dielectric for $t_{\text{oxide}} = 80$ Å, B: Variation of $\beta_k$ and $\beta_{k,\text{plane}}$ in Eq. 5.3.1 and Eq. 5.3.1 with thickness of dielectric layer ($V = 8$ V, $R = 100$ Å)

Fig. 5.10A shows the comparison between the force on metal and dielectric for confocal hyperboloid geometry. The factor $\beta_k$ can be compared with the corresponding factor for a planar configuration consisting of two parallel plane conducting surfaces separated by a distance ‘$s$’ having the parallel plane dielectric layer of thickness ‘$t_{\text{oxide}}$’ between them. This factor is given by

$$\beta_{k,\text{plane}} = \frac{ks}{ks - (k - 1)t_{\text{oxide}}} \quad (5.2)$$

The comparison between variation in $\beta_k$ and $\beta_{k,\text{plane}}$ in Eq. 5.3.1 and Eq. 5.3.1 with the thickness of dielectric layer is shown in Fig. 5.10B which is observed to increase with the thickness.

5.3.2 Experimental

The results reported in this paper were taken in non-contact mode of AFM using an in-house modified Burleigh AFM head (Metris 2000) in entirely ambient condition. All the electrostatic force measurements were performed using a stylus cantilever made up of heavily doped Si having resistivity of 0.01 Ω-cm (Mikro-Masch NSC36). The dynamic in-situ measurement of cantilever dynamics yielded
resonance frequency and force constant of 95 KHz and 0.45 N/m respectively. The present study mainly focused on behavior of the electrostatic force on polarizable dielectric of known dielectric constant. Highly conducting Si(111) of P-type (resistivity: 0.02 Ω-cm) wafer with 25 Å, 50 Å, 80 Å, 160 Å SiO$_2$ (k = 4.5) thicknesses were used as substrate. SiO$_2$ has been grown by thermal oxidation process. Thermal oxidation is a way to produce a thin layer of oxide on the surface of a wafer. The technique forces an oxidizing agent to diffuse into the wafer at high temperature and react with it. The rate of oxide growth is often predicted by the Deal-Grove model. Thermal oxidation of silicon is usually performed at a temperature between 800 and 1200°C, resulting in so called High Temperature Oxide layer (HTO). It may use either water vapor (usually UHP steam) or molecular oxygen as the oxidant; it is consequently called either wet or dry oxidation. The samples were provided by NUS institute, Singapore.

Before the electrostatic force measurements, samples were investigated using Scanning Electron Microscopy (SEM) and AFM to confirm uniform coverage of SiO$_2$. Prior to the experiment, the silica gel was placed in AFM chamber near the tip-sample assembly to avoid the contribution from residual water layer. Before the experiments in non-contact mode, contact mode force curves were obtained to estimate the zero points of X and Y axes which are tip-sample distance and force respectively. These are the points at which the force on the cantilever becomes zero during the approach. Current limiting resistor was used in series with the tip-sample junction to avoid the excessive current flow due to physical contact of the tip with sample which may lead the modification of the tip/sample surface. Then the system is locked at position below the resonant frequency of the cantilever which is usually done in non-contact mode for highest sensitivity [21].
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5.3.3 Results and discussion

The total force on the cantilever in the present case is given by

$$F_{total} = F_{dc} + F_0 \sin \omega t$$  \hspace{1cm} (5.2)

where,

$$F_{dc} = \frac{1}{2} \left( \frac{dC}{ds} V_b^2 \right)$$ \hspace{1cm} (5.2)

and $F_0$ is the amplitude variation due to cantilever oscillation, $C$ is the static capacitance. By monitoring the dc shift of the cantilever it is possible to measure its static deflection as a function of distance. Fig. 5.11 refers to typical force-distance curves at different bias recorded in oscillating cantilever mode. It can be seen that all the curves in Fig. 5.11 show two distinct regimes. Far away from the

![Figure 5.11: Typical force-distance curves obtained from mean deflection of the cantilever at different bias for oxide layer of thickness 160 Å. (taken in dynamic mode)](image-url)
surface the curve is slowly varying which we attribute to the attractive part of the potential. As the cantilever approaches to the surface, the behavior changes abruptly from slowly varying to fast varying at a distance which decreases with the decrease in bias voltage. While plotting Fig. 5.12 only slowly varying part is considered to eliminate the contribution due to repulsive part of the potential. The tip was positively biased while keeping the sample at ground during the experiment. Since the distance between tip and sample in non-contact mode is \( \sim 200 \, \text{Å} \) or more, high voltage bias is required to get measurable deflection. The dc shift in the detector signal is a measure of static deflection of the cantilever and is plotted against distance to obtained force curves at constant bias (8 V) for different thickness of dielectric layer.

Fig. 5.12A shows the force-distance curves obtained from mean deflection of the cantilever in dynamic mode for different thickness of dielectric layer at constant bias. Inset of Fig. 5.12 clearly shows that the observed force increases with the thickness of dielectric layer. The thickness dependency of the force curves is shown in inset of Fig. 5.10A and obeys \( F = k t_{oxide}^2 \) dependence. The experimental results are compared with the theoretical behavior for different tip-sample geometry in Fig. 5.10B. The data is fitted using Levenberg-Marquardt method [12] for \( r_{\text{max}}/R = 1.9 \). From the fitted data it can be seen that the general behavior of the electrostatic force-distance curves for polarizable dielectric is in reasonably good agreement with the experimental data for the range of distances investigated in the present work.

It is of interest to compare present results with other approximations used in the literature. For instance, Hao et al. have studied Coulomb forces by modeling the tip-sample geometry as a sphere-on-flat surface [22]. For a special case of parallel plate approximation of sphere-plane configuration for very small distances \( (R \gg s) \) the force can be written as

\[
F_{\text{sp}} = \pi \varepsilon_0 V^2 \left( \frac{R}{s} \right)
\]  

(5.2)
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Figure 5.12: A: Comparison of experimental data with Eq. 5.3.1 for different thicknesses at constant bias, inset shows the plot of force versus thickness at constant distance, B: Comparison of force curves for metallic tip-insulating surface for different geometries ($t_{\text{oxide}} = 80 \, \text{Å}, R = 100 \, \text{Å}, V = 8 \, \text{V}$)

while for larger distances ($R \ll s$) it becomes

$$F^{sp} = \pi \varepsilon_0 V^2 \left( \frac{R}{s} \right)^2$$ \hspace{1cm} (5.2)

Fig. 5.4 to highlight the difference between confocal hyperboloid and popularly used sphere-plane configuration [8, 16]. From the figure it is seen that in sphere-plane approximation for $R \ll s$ there is stiff variation in the force for shorter distance and very weak distance dependence for larger distance. However for confocal hyperboloid geometry proposed in the present work, the change in from long distance to short distance behavior is less abrupt and it is in good agreement with experimentally observed data (Fig. 5.10A). Since the radius of the tip is taken as 100 Å, the Eq. 5.3.3 is not applicable for the data in Fig. 5.10B. In this work we were able to get phase versus distance curves at different bias for each thickness of $\text{SiO}_2$. Fig. 5.13 shows one of the phase-distance curve taken at different applied voltages. Form the Fig. 5.13 it can be seen that the curvature in the phase curve is increases with the applied voltage which can be explained using the theory of electrostatic force gradient (dF/ds). The phase shift due to electrostatic force gradient is given by [23],
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Figure 5.13: Phase versus distance curves taken on $SiO_2$ with thickness 2.5 nm for different bias voltages.

\[ \Delta \phi = -\arcsin \left( \frac{Q}{k} \frac{dF}{ds} \right) \]  \hspace{1cm} (5.2)

since, electrostatic force is given by

\[ F = \frac{1}{2} \frac{d^2C}{d^2s} V^2 \]  \hspace{1cm} (5.2)

Eq. 5.3.3 becomes [23]

\[ \Delta \phi = -\arcsin \left( \frac{Q}{2k} \frac{d^2F}{d^2s} V^2 \right) \]  \hspace{1cm} (5.2)

From Eq. 5.3.3 it is clear that the phase shift is a function of applied potential difference between tip and sample.
5.4 Conclusion

In conclusion, an attempt has been made to investigate the electrostatic interaction between conducting tip and insulating surface. A formula for electrostatic force between conducting spherical tip and the insulating surface in proximity has been discussed. Experimental data was obtained on freshly cleaved mica surface and compared with sphere-on-plane approximation. Also a new type of hybrid cantilever has been developed. It was used to investigate the electrostatic interaction between both metallic and insulating surfaces with conducting tip. Since it has very low resonant frequency, it can be used only to study the forces between tip and sample. However, a formula has been derived for the electrostatic force between the conducting tip near metallic surface coated with a layer of polarizable dielectric by exploiting the fact that the tip-sample configuration can be represented as confocal hyperboloid surfaces of revolution in a prolate spheroidal coordinate system. The general behavior of dependence of force on tip-sample separation and thickness of dielectric film has been experimentally verified using a Conducting Atomic Force Microscope. The results are in better agreement over a wide range of distances than the widely used sphere-on-plane approximation.
Bibliography


