Measurement of the Streaming Potential and Streaming Current near a Rotating Disk to Determine Its Zeta Potential

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Methodology for determining the zeta potential of a disk-shaped sample by both streaming potential and streaming current measurements is presented. Integration of Laplace's equation within one radius of the disk surface revealed that the streaming potential decreased strongly in the surface normal direction. With this solution, the zeta potential can be calculated from measurements of the streaming potential near the surface of the disk provided the position of the working electrode near the disk surface is known. Determining the zeta potential of a disk-shaped sample by means of streaming current measurements required determination of a current collection efficiency because not all the streaming current from a disk flows through the auxiliary electronic current path. While the working electrode near the disk should be pointlike, several possible variants on counter electrode shape and size were explored. Although the current collection efficiency was only a few percent in each case, the measured current was of 10 nA order. The current collection efficiency depended only on system geometry and was independent of a disk's zeta potential and solution concentration. Streaming current measurements of zeta potential on silicon wafers in potassium chloride solutions up to 10 mM agreed well with published values.

Introduction

The electric potential at the surface of shear relative to electrically neutral solution far away is often called the "zeta potential". Measuring the zeta potential of particles is most common, but the zeta potential of planar surfaces is also important. The biocompatibility of polymers used in medical devices depends on the polymer's zeta potential. Measurements of zeta characterize the adsorption of proteins or surfactants to solid surfaces.[1−8] In chemical-mechanical polishing of silicon wafers, particles adsorb to the surface during polishing due to the opposite zeta potentials of the surface and the polishing particles. After polishing, increasing the pH such that the wafer and particles both have a negative zeta potential can cause the particles and wafer to repel one another. The zeta potential can be measured to ensure the desorption of polishing particles.[7,8]

A popular method for measuring the zeta potential of planar surfaces relies on flow in a channel between parallel plates. Two identical plate samples, or two different plates where the zeta potential of one plate is known, form the channel. Pressure driven flow through the capillary moves the charge in the diffuse layer on each plate, thereby producing a convected ionic current. One measures either a streaming potential or a streaming current for instance by means of two electrodes on opposite ends of the capillary connected to an external meter having either a high or low impedance, respectively. The zeta potential is proportional to the measured streaming potential or streaming current.[1−5]

Sides and Hoggard[6] recently described a zeta potential measurement method based on a rotating disk. Solving Laplace's equation in the vicinity of the disk using a boundary condition of zero net current flow from the disk surface, they calculated streaming potential as a function of rotation rate, fluid properties, and zeta potential of the disk. The theory revealed effective locations for the electrodes, i.e., one electrode placed on the axis of the disk near the disk surface and the other placed far from the disk. Agreement between theory and experiments was excellent when the zeta potential of the surface was used as a fitting parameter. This work showed that the zeta potential can be calculated using streaming potential measurements in aqueous salt solutions with concentrations of 0.1 mM on 50 mm diameter disks. The streaming potentials were much less than 1 mV at higher concentrations, which made determination of the zeta potential problematic under these conditions.

The present contribution adds new theory and new methodology to the previous work. The theory is extended by solving Laplace's equation in the bulk solution away from the surface of the disk, which allows calculation of the streaming potential at any position in the vicinity of the disk. Experimental results are presented to verify the theory. Additionally, we demonstrate means for measuring streaming current. An experimental relationship between the zeta potential and the measured streaming current is found for several variants of the apparatus.

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Theory

Calculation of the Streaming Potential away from the Disk. Outside the electric double layer, the electrolyte solution can be treated as electrically neutral so that the electrostatic potential ϕ satisfies Laplace's equation. The streaming potential next to a rotating disk can be obtained by integrating Laplace's equation in rotational elliptical coordinates subject to appropriate boundary conditions. In rotational elliptical coordinates, Laplace's equation is given as

$$\nabla^2\phi = \frac{\partial}{\partial\xi}\left[(1+\xi^2)\frac{\partial\phi}{\partial\xi}\right] + \frac{\partial}{\partial\eta}\left[(1-\eta^2)\frac{\partial\phi}{\partial\eta}\right] = 0 \quad (1)$$

Rotational elliptical coordinate variables η and ξ are related to cylindrical coordinate variables by $z = R\eta\xi$ and $r = R[(1+\xi^2)(1-\eta^2)]^{1/2}$. $\eta = 0$ is off the disk in the plane that includes the disk. $\eta = 1$ is the axis of the disk. $\xi = 0$ is on the disk and $\xi = \infty$ is far from the disk. Newman[9-11] showed that Laplace's equation is separable in this coordinate system

$$\phi = \sum_{n=0}^{\infty} B_n P_{2n}(\eta) M_{2n}(\xi) \quad (2)$$

where P_{2n} are even Legendre polynomials, and M_{2n} is a Legendre function of imaginary argument. M_{2n} has a value of unity on the disk surface and zero at infinity.

Appropriate boundary conditions are as follows

$$-\frac{\kappa}{R\eta}\frac{\partial\phi}{\partial\xi}\bigg|_{\xi=0} = i_z = \frac{2\epsilon\epsilon_0 a\Omega^{3/2}\zeta}{\nu^{1/2}}\left[1 - \frac{1}{2\eta}\right] \quad (3)$$

$$\frac{\partial\phi}{\partial\eta}\bigg|_{\eta=0} = 0 \quad (4)$$

$$\phi|_{\xi\to\infty} = 0 \quad (5)$$

$$\phi|_{\eta=1} = \text{well behaved} \quad (6)$$

where i_z is the current density normal to the disk surface,[6] ϵ is the dielectric constant of the solution, ϵ_0 is the permittivity of free space, a is a constant equal to 0.510 23,[6,12-14] Ω is the rotation rate, ζ is the zeta potential, κ is the conductivity of the solution and ν is the kinematic viscosity. Equation 3 specifies the current density distribution on the active portion of the disk ($z = 0$ and $r < R$) as determined by Sides and Hoggard.[6] The remaining boundary conditions resemble those used by Newman.[10] Equation 4 represents zero current normal to the plane of the disk for $z = 0$ and $r > R$; eq 5 sets the reference state for potential as the bulk solution far from the disk while eq 6 is sufficient to ensure $\partial\phi/\partial r = 0$ at $r = 0$ so that *iso*-ϕ contours will be kink-free on the axis (a typical symmetry condition in cylindrical coordinates). Equation 6 is satisfied by choosing the Legendre function $P_{2n}(\eta)$ of the first kind, zero order with integer degree (also known as the Legendre polynomials); eq 4 is satisfied by choosing this integer order to be even; hence $P_{2n}(\eta)$. Satisfying eq 5 places constraints on the function $M_{2n}(\xi)$:[10]

$$M_{2n}(0) = 1 \quad (7)$$

$$M'_{2n}(0) = -\frac{2}{\pi}\frac{(2^n n!)^4}{[(2n)!]^2} \quad (8)$$

where $M'_{2n}(0)$ is the derivative of $M_{2n}(\xi)$ with respect to ξ evaluated at $\xi = 0$.

Sides and Hoggard solved for the coefficients, B_n using eqs 2, 3, 7 and 8. The coefficients are given as

$$B_n = \frac{-2\epsilon\epsilon_0 aR\Omega^{3/2}\zeta}{\kappa\nu^{1/2}}\frac{1}{M'_{2n}(0)}\left[\frac{\int_0^1\left(\eta - \frac{1}{2}\right)P_{2n}(\eta)d\eta}{\int_0^1[P_{2n}(\eta)]^2\,d\eta}\right] \quad (9)$$

To solve for ϕ away from the disk surface, $M_{2n}(\xi)$ must be solved using eq 10 as derived from eq 1 using separation of variables with a separation constant equal to $2n(2n + 1)$.

$$\frac{d}{d\xi}\left[(1+\xi^2)\frac{dM_{2n}(\xi)}{d\xi}\right] = 2n(2n+1)M_{2n}(\xi) \quad (10)$$

A power series solution can be obtained in the form

$$M_{2n}(\xi) = \sum_{k=0}^{\infty} c_k\xi^k \quad (11)$$

Substituting eq 11 into eq 10 and solving leads to the recursion formula

$$c_{k+2} = \frac{2n(2n+1) - k(k+1)}{(k+2)(k+1)}c_k \quad (12)$$

Applying eqs 7 and 8 leads to the solution of all the constants with $c_0 = 1$ and $c_1 = M'_{2n}(0)$. This solution converges for values of $\xi \le 1$, which corresponds to a distance of one radius in the surface normal direction on the disk axis. This radius of convergence is characteristic of the power series solution of Legendre's equation.[15] In this paper, the values of n and k used are 20 and 1000, respectively.

Measurement of Streaming Current. One measures a streaming current by offering the convected current an electronic auxiliary path through an ammeter to close the "circuit"; this is accomplished with near perfect collection efficiency in a capillary-based apparatus because the ohmic resistance of the flow channel is typically high relative to the resistance for flow through the auxiliary circuit. The rotating disk, however, is not ideally suited for a streaming current measurement because the ionic and auxiliary electronic paths compete for current. One therefore must use a current collection efficiency when using the rotating disk in a streaming current measurement. Some fraction of the total streaming current flowing from the disk travels through the current collection system, including the ammeter. Theory[6] shows that a uniform

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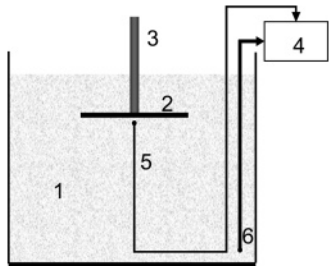

Figure 1. Schematic of the streaming potential experimental apparatus. Electrolyte (1) was poured into a 2 L beaker. A disk (2) was prepared, affixed to a rotator (3), and spun at various rates. A lead (5) from the working electrode near the disk connected to the positive terminal of a Keithley Instruments Electrometer (4). A lead from a counter electrode (6) connected to the negative terminal of the electrometer. The measured voltage depended on the rotation rate as described in the text.

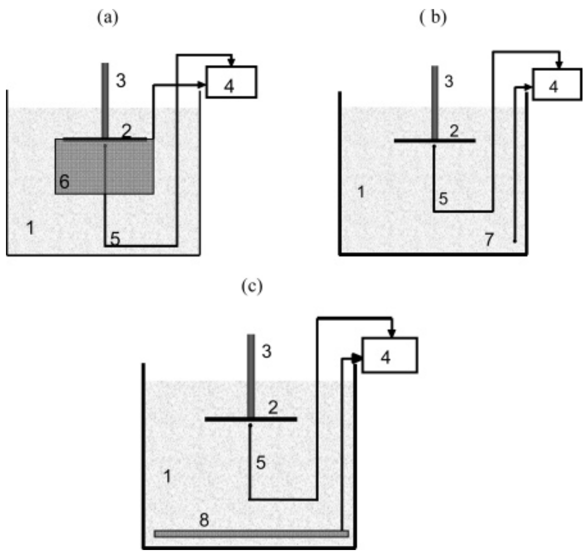

Figure 2. (a,b,c) Schematics of the streaming current experimental apparatuses. In each Electrolyte (1) was poured into a beaker. A disk (2) was prepared, affixed to a rotator (3), and spun at various rates. A lead (5) from the working electrode near the disk connected to the positive terminal of a Keithley Instruments Electrometer (4). A lead from a counter electrode (6−8) was connected to the negative terminal of the electrometer. The shape of this counter electrode was different in each apparatus. Figure 2a shows a "skirt" electrode (6); 2b, a wire electrode identical to that in Figure 1 (7); 2c, a plate electrode (8). The size of the beaker was 2 L for 2a and 2b, and was 400 mL for 2c. In each experiment, the 2/3 power dependence on rotation rate was observed as described in the text.

current density flows from the surface of the disk when it is rotated, given by

$$i_z = \frac{2\epsilon\epsilon_0 a \Omega^{3/2}\varsigma}{\nu^{1/2}} \qquad (13)$$

Most of this current returns to the disk surface without passing through the ammeter that connects electrodes positioned as shown in Figure 2. A current collection efficiency can be defined as follows

$$\mathrm{Eff} = \frac{I_{\mathrm{meas}}}{i_z \pi R^2} \qquad (14)$$

where I_{meas} is the measured current. When Eff is known, ζ can be calculated via eqs 13 and 14. If Eff does not vary with conductivity and the magnitude of ζ, then Eff only depends on the geometry of the system.

Experimental Section

The streaming potential measurement apparatus appears in Figure 1. A 50-mm disk sample is attached to a spindle, immersed in electrolyte held by a 2 L glass vessel, and rotated at arbitrary rates between zero and 2500 rpm. Two Ag/AgCl electrodes were connected to a Keithley Instruments Electrometer (Model 614). The counter electrode attached to the negative terminal of the electrometer was placed at the bottom of the vessel far from the disk surface.[6] The working electrode attached to the positive terminal of the electrometer was located one millimeter from the disk surface on the axis of the disk.[5,6] This electrode was an exposed Ag wire tip coated with AgCl. The position of the working electrode could be precisely controlled in both the radial and vertical directions, which allowed for tests of the theory relating the streaming potential to the position in the solution. Voltage measurements were filtered using a low pass filter to remove erroneous oscillating potentials.

The apparatus for streaming current measurements appears in Figure 2. A working Ag/AgCl electrode is placed on the axis of the disk near the disk surface and attached to the positive terminal of the same Keithley electrometer operating in current mode.[5] Three different counter electrode designs were investigated. A 2.5 in. diameter Ag/AgCl cylindrically shaped counter electrode in the form of a "skirt" was attached to the negative lead as shown in Figure 2a. The top of the "skirt" electrode was at the same height as the disk sample. Both the top and bottom of the skirt were open. The second design of the counter electrode was a wire tip placed far from the disk (Figure 2b), which duplicated the design for streaming potential measurement. The third counter electrode was a flat plate placed in the bottom of the cell (Figure 2c). Unlike the potential measurements, current measurements were not filtered.

To make the electrodes, 99.99% pure twelve gauge silver wire was coated with polyolefin heat shrink tubing. Approximately 1 mm of the wire was exposed and treated according to a recipe combining the methods of Ives and Janz and Westermann-Clark.[16,17] Two coated wires were soaked for 1 h in a concentrated ammonia solution. They were then washed with deionized water, dipped in concentrated nitric acid to roughen the surface, and placed in a 0.1 M HCl solution. A 0.1 mA current was passed for 1 h by a current source through two silver wires connected in parallel at the positive terminal to a nitric acid cleaned copper wire at the negative terminal. This resulted in a plum colored AgCl coating. The electrodes were then rinsed and soaked in deionized water for 24 h before being tested on the electrometer. Satisfactory electrode potential differences fluctuated less than 0.1 mV and ideally had an open circuit potential difference less than 1.0 mV. To make the Ag/AgCl "skirt" electrode, a sheet of 99.99% silver was formed into a cylinder with a height of 75 mm and a diameter of 63 mm. The same procedure was followed as above except a 30 mA current was passed for 24 h. For the plate electrode, a current of 20 mA was passed for 4 h. The colors of the electrodes when finished were identical to the color of the wires.

Disks having a diameter of 50 mm were used in all experiments. In the streaming potential experiments, a silicon wafer was cleaned by soaking 20 min in Chromerge and 5 min in deionized water. This wafer is called the "cleaned" silicon wafer. Other silicon wafers tested in streaming current measurements were only rinsed in deionized water after being taken from the packaging; these are called "rinsed" wafers. Also used were an indium tin oxide coated glass disk washed in ethanol followed by a deionized water rinse and a sapphire disk soaked 20 min in Chromerge followed by a deionized water rinse.

Results and Discussion

Streaming Potential Calculations. Figure 3 shows a contour plot of the streaming potential as a function of

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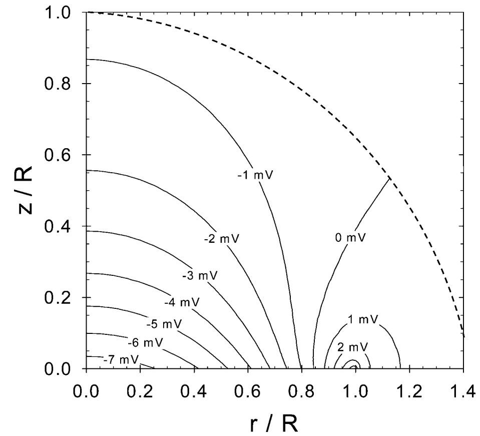

Figure 3. Streaming potential as a function of position in the solution as predicted by theory. The zeta potential is −146 mV, the rotation rate is 1500 rpm, the disk diameter is 50 mm, and κ is 1.45 μS/cm. *z*/*R* represents the axial direction. *r*/*R* represents the radial direction. The dashed line indicates the radius of convergence ($\xi = 1$) for the power series solution of $M_{2n}(\xi)$ above which the solution diverges. The magnitude of the potential is greatest on the axis of the disk on the disk surface ($z/R = r/R = 0$). As is shown, the potential has a region of positive and negative potential. These opposite potentials result from the boundary condition of no net current flowing from the disk surface. This plot reinforces the conclusion of Sides and Hoggard[6] that the optimum place to make the streaming potential measurement is on the axis of the disk near the disk surface.

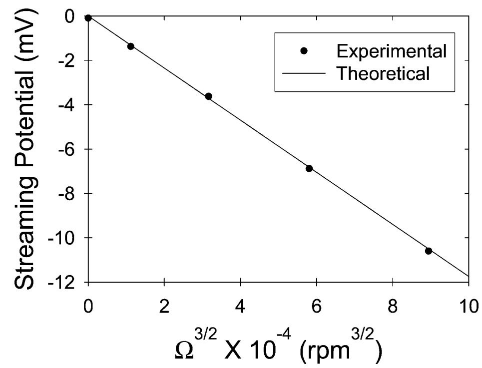

Figure 4. Streaming potential as a function of rotation rate raised to the 3/2 power on a silicon wafer. The solid circles are experimental measurements made in an aqueous KCl solution with a conductivity of 1.45 μS/cm. The solid line is a least-squares fit of the experimental data. The measurement was made on the disk axis 1 mm from the disk surface. The rotation rate was varied from 0 to 2000 rpm. The zeta potential calculated from theory using the slope of the line is −146 ± 1 mV.

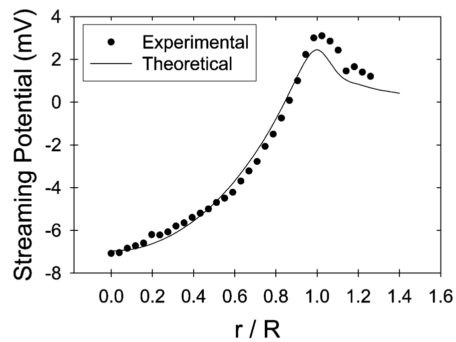

Figure 5. Streaming potential as a function of radial position on a silicon wafer. The conditions are the same as in Figure 4 except the rotation rate is held constant at 1500 rpm. The solid circles were measured experimentally by Sides and Hoggard near the surface of the disk. The solid line is calculated by theory 1 mm from the disk surface and corrects[23] the calculation of Sides and Hoggard[6] near $r/R = 1.0$. The corrected calculation captures the rise and fall of the streaming potential near the disk edge. The experimental data deviates from the theory near the edge of the disk because edge effects are not included in the flow theory.

position within one radius of the disk surface calculated from theory using a zeta potential of −146 mV, a rotation rate of 1500 rpm, and a solution conductivity of 1.45 μS/cm. The disk surface lies along the abscissa and the axis of the disk is at the origin. Electrolyte extends upward away from the disk. The contour of zero streaming potential extends vertically from the disk and flares out away from the axis. Near the disk surface, the equipotential lines are nearly vertical near the outer part of the disk but are nearly horizontal near the axis. This figure has consequences for the measurement of streaming potential; it shows that the expected streaming potential depends strongly on the gap between the disk and the working electrode of Figure 1. We tested this sensitivity as described in the next section. Also it shows that measurement of streaming potential near the edge of the disk is problematic.

Streaming Potential Measurements. On the basis of eqs 2 and 9, the streaming potential is expected to be proportional to $\Omega^{3/2}$. Figure 4 shows that this is what was found for a cleaned silicon wafer in a 1.45 μS/cm KCl solution.[6] Comparing the slope of a regression of the data in Figure 4 to the corresponding expectation from eq 2 and 9, the zeta potential was deduced to be −146 mV. The results shown in Figure 4 are characteristic of streaming potential measurements made with one working electrode placed on the axis of the disk near the disk surface and a counter electrode placed far from the disk surface. Figure 5 shows the radial dependence of the streaming potential near the surface of the disk with the rotation rate held constant at 1500 rpm. This graph extends the similar plot (Figure 6 of Sides and Hoggard[6]) beyond the disk edge and corrects an error in that illustration.[23] The characteristic regions of positive and negative potential are shown. The theory captures well the complicated behavior of the streaming potential near the disk edge. Sides and Hoggard concluded that on the axis very near the rotating disk was the optimum place to make streaming potential measurements because the streaming potential is insensitive to *r* there. By contrast, measurements of streaming potential near the outer edge of the rotating disk were small and quite sensitive to position.

Using the same wafer and KCl solution, we measured the *z* dependence of the streaming potential on the axis of rotation ($r = 0$). Figure 6 shows the streaming potential as a function of distance from the disk in the surface normal direction along the disk axis. The theoretical line is calculated from theory using the “fit” zeta potential of −146 mV, a constant rotation rate of 1500 rpm, and eqs 2, 9, 11, and 12. The solid curve, which has no adjustable

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(22) Hunter, R. J.; Wright, H. J. L. *J. Colloid and Interface Sci.* **1971**, *37*, 564−580.
(23) The calculated line in Figure 6 of Sides and Hoggard[6] contained an error that caused the theoretical line shown in that Figure to deviate positively from the correct line at higher values of the radius. The theoretical line shown in Figure 5 of the present contribution corrects this error, bringing theory and experiment into closer agreement.

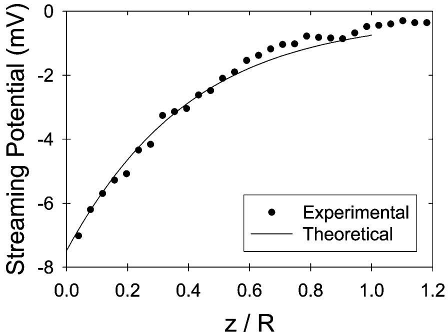

Figure 6. Streaming potential as a function distance from the disk surface along the disk axis. The solid circles are experimental measurements and the theoretical line is calculated using the zeta potential calculated in Figure 3. The conditions were the same as in Figure 4 except the rotation rate was held fixed at 1500 rpm. The theoretical solution converges for $z/R \le 1$. At $z/R = 1$, the streaming potential is equal to 9.5% of the potential at the surface of the disk. Care must be taken to measure the distance of the working electrode to the disk surface because of the slope of the potential near the surface.

parameters, agrees well with the experimental data, thus confirming the theory of eqs 2, 9, 11, and 12. Although the steepest portion of the curve in Figure 6 occurs near $z = 0$, this represents the best place to make the measurement because the streaming potential is largest there. Figures 3−6 show that with zeta potential as the only unknown, the theory presented can be used to calculate the zeta potential from streaming potential measurements anywhere in the vicinity of the disk as long as the counter electrode is far from the disk and the position of the working electrode is known. In all other experiments presented in this paper, this location of the working electrode is on the axis of the disk and 1 mm from the disk surface.

Streaming Current Measurements. There are limits, however, to streaming potential measurements. When a 50 mm diameter disk with a zeta potential of −60 mV is tested in 0.1 mM KCl solution, the streaming potential measured at 2500 rpm is less than a mV, which means that noise in the measurement became comparable to the signal. Thus streaming potential measurements with a 50 mm disk became more susceptible to error above approximately 1 mM aqueous salt solutions. This limitation on use of streaming potentials was a motivation to make a streaming current measurement. In a parallel plate capillary, streaming current measurements are conductivity independent (except for conductivity's effect on ζ); our hypothesis was that the same would be true for streaming current measurements on the rotating disk.

Using the apparatus in Figure 2a, we measured the streaming current near the surface of a rinsed silicon wafer as a function of rotation rate in a 10^{-6} M KCl solution. The measured streaming current as a function of rotation rate from one experiment appears in Figure 7. As with the streaming potential measurements, the collected streaming current was proportional to the 3/2 power of the rotation rate in accordance with eq 13. The measured current was of 10 nA order, but the total current $\pi R^2 i_z$ calculated from eq 13 was of microamp order. Because only a fraction of the total streaming current is collected, eq 13 cannot be used to calculate the zeta potential. Instead, a current collection efficiency is defined (eq 14) and its values for the three variants of counter electrodes shown in Figure 2 were determined experimentally.

To determine the current collection efficiency, both streaming potential and streaming current measurements are necessary. We first measured the streaming potential

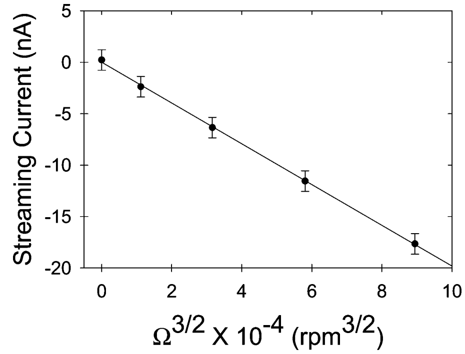

Figure 7. Streaming current as a function of rotation rate raised to the 3/2 power. Using a working electrode placed on the axis of the disk near the disk surface and a “skirt” shaped counter electrode around the outside of the disk (Figure 2a), the streaming current on the order of 10 nanoamps was measured. The sample is a deionized water washed silicon wafer in a 10^{-6} M KCl solution. The rotation rate was varied from 0 to 2000 rpm. Like the streaming potential, the streaming current is proportional to rotation rate to the 3/2 power. The solid circles are experimental measurements and the line is a linear fit to the slope of the data. The error bars result from fluctuations in the current due to measurement of an unfiltered signal.

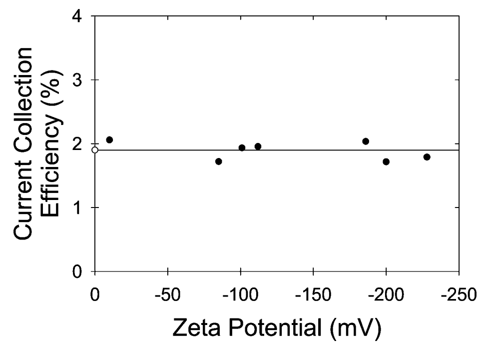

Figure 8. Current Collection Efficiency as a function of zeta potential. Silicon wafers, an indium tin oxide coated glass disks, and a sapphire disk are tested to calculate the current collection effiency over a range of zeta potentials. The line corresponds to a collection efficiency of 1.9%. The zeta potentials were calculated from streaming potential measurements in 10^{-5} M KCl solutions. The streaming current measurements were made in the same solution as the streaming potential measurement. The setup for this experiment is shown in Figure 2a.

of a disk in 10^{-5} M KCl to determine ζ. The streaming current was then measured as a function of rotation rate in the same solution and the efficiency was calculated from eq 13 and 14. If the current collection efficiency determined in the described manner is robust, it should depend neither on the value of the zeta potential nor on the concentration of the electrolyte.

First, using the apparatus shown in Figure 2a, the current collection efficiencies were determined for disks with varying zeta potentials. The disks tested were silicon, indium tin oxide, and sapphire. The calculated Eff was plotted in Figure 8 against the zeta potential as described above. The results appearing in Figure 8 show that the current collection efficiency was independent of the magnitude of zeta from 0 to −250 mV. We also determined the collection efficiency of the apparatus in Figure 2c for solutions of various KCl concentrations. The results appearing in Figure 9 show that the collection efficiency was independent of concentration in the range of concentrations shown. Thus the collection efficiency defined by eqs 13 and 14 is a valid method for converting streaming current measurements to zeta potential in the range of conductivities tested.

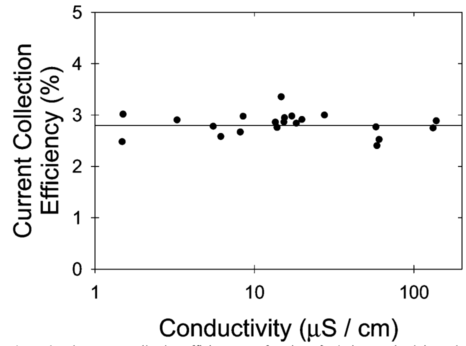

Figure 9. Current collection efficiency as a function of solution conductivity. The streaming current and potential were measured using the setup shown in Figure 2c in KCl solutions. The solid line corresponds to Eff = 2.8%. This figure shows Eff to be constant over the range of conductivities that can be measured using streaming current and streaming potential measurements. Using this efficiency, the zeta potential can be calculated at higher solution conductivities using streaming current measurements.

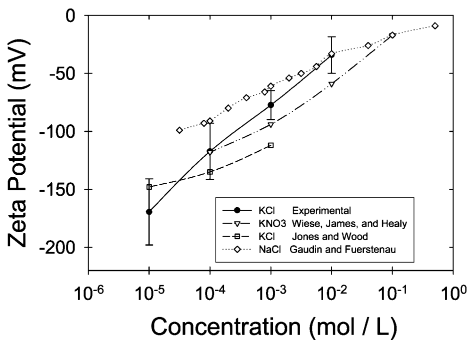

Figure 10. Zeta potential of silicon dioxide as a function of aqueous salt concentration. The solid circles with error bars are zeta potentials calculated from streaming current measurements on three deionized water rinsed silicon wafers in KCl rotated from 0 to 2500 rpm. These data are compared to other zeta potential measurements made in dilute salt solutions at neutral pH found in the literature: the open squares are results of Jones and Wood[18] in KCl solutions using streaming potential measurements across a cylindrical, vitreous silica capillary, the open triangles are the results of Wiese et al.[19,20] in KNO_3 solutions using the same technique as Jones and Wood, and the open diamonds are data of Gaudin and Fuerstenau[21,22] in NaCl solutions using streaming potential measurements across a porous plug of silica. The plot shows decent agreement of streaming current measurements using a rotating disk with values in the literature using other techniques.

The current collection efficiency was measured for each apparatus depicted in Figure 2. The value is dependent on the placement and shape of the counter electrode. For the setups shown in Figure 2a−c, the current collection efficiency was found to be 1.9 ± 0.1%, 0.76 ± 0.1%, and 2.8 ± 0.2%, respectively. The streaming current of a rotating disk can thus be used to determine the zeta potential within approximately 10% of its value.

Using the apparatus shown in Figure 2a and a current collection efficiency of 1.9%, the zeta potential of a silicon wafer was calculated from streaming current measurements in KCl concentrations from 10^{-5} to 10^{-2} M and eqs 13 and 14. These data appear in Figure 10 alongside the results of and Jones and Wood,[18] Wiese et al.,[19,20] and Gaudin and Fuerstenau[21,22] who measured streaming potential in capillaries in various salt solutions at neutral pH. The zeta potentials determined with the rotating disk apparatus show reasonable agreement with the reported results. This agreement and the evidence shown previously demonstrate that the use of a current collection efficiency is a valid method for converting streaming current measurements to zeta potentials in the rotating disk approach.

Conclusion

Streaming potential can be measured near a rotating disk in solutions of low conductivity. It is important that a working electrode is placed on the axis of the disk and that the gap between this electrode and the disk is small and known because the streaming potential measurement depends strongly on this gap. Streaming potential measurements can be used to calculate the zeta potential of any disk-shaped sample because of the complete theory relating the two, but practicalities of measurement limit the concentration of test solutions to approximately 1 mM and below.

Streaming current measurements on a rotating disk cannot be directly related to the zeta potential by theory because only a fraction of the total current flows through the ammeter. Nevertheless, a current collection efficiency that depends on the particular geometry of the apparatus in use can be deduced. The current collection efficiency was shown to be independent of zeta potential and solution conductivity below 1 mM.

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