

The Effect of Film Thickness on Contact Electrification

S. L. BURKETT,^{1,*} E. M. CHARLSON,² E. J. CHARLSON,² and H. K. YASUDA³

¹Department of Electrical Engineering, University of Alabama, Tuscaloosa, Alabama 35487; ²Department of Electrical Engineering, University of Missouri, Columbia, Missouri 65211; and ³Department of Chemical Engineering, University of Missouri, Columbia, Missouri 65211

SYNOPSIS

Contact electrification experiments have been performed for the purpose of studying the effect of varying film thickness on charge transfer during metal-insulator contact. Thin films of plasma polymerized methane are deposited on silicon substrates using a magnetically enhanced glow discharge system. Film uniformity across the wafer is verified by ellipsometric techniques. Variations in film thickness from approximately 100 to 600 Å result in a variable amount of charge transfer when the films come in contact with a metal probe. Charging of the polymer film increases with increasing film thickness up to a limiting thickness of approximately 375–400 Å. Similar results are obtained when various substrate treatments are performed previous to film deposition and charge measurements are obtained as a function of film thickness. Contact electrification measurements show the metal-insulator contact is influenced by the insulator/substrate interface up to the same limiting film thickness (375–400 Å). The instrumentation used in this series of experiments is based on measurement of the currents associated with the contact and subsequent separation of the surface state systems of a metal and an insulating polymer. This technique relies on measurement of currents in the picoampere range and appears to be a novel method to experimentally determine charge penetration depth. © 1996 John Wiley & Sons, Inc.

INTRODUCTION

For some time, investigators have been attempting to determine the nature of the charge transfer that takes place when two dissimilar materials are brought into contact and subsequently separated. There are a variety of opinions as to whether electrons, ions, or material transfer is responsible for charge transfer and whether this is a bulk or surface effect. There has also been extensive experimental investigation to determine the depth of charge penetration.^{1–9} An excellent review by Lowell describes research performed in the general area of contact electrification.¹⁰ Instrumentation has been developed in our laboratory for the purpose of studying contact electrification. The technique is based upon measurement of small currents that occur for contacts made between a metal and an insulating film and the small currents that occur upon their sub-

sequent separation. The measurement technique, termed “contact-separation,” has been used to characterize polymers formed by plasma polymerization. Validity of this technique has been established by acquiring “contact-separation” measurements in conjunction with conventional measurement techniques for these dielectric materials.¹¹

One of the major problems in the study of contact electrification is the fact that most investigators have been unable to achieve reproducible results for charge measurements associated with metal-insulator contacts. This results in experimental data which are difficult to interpret. The problem of charge variability has been resolved for plasma polymer films on silicon substrates using the contact-separation technique.¹² The progress in reproducibility of charge measurements is believed to be due to the fact that the films are uniform in thickness, deposited on smooth substrates, with controlled and reproducible deposition conditions. Once reproducible charge measurements were obtained, experimental studies were performed to evaluate the effect of variations in film thickness on charge mea-

* To whom correspondence should be addressed.

surements. Charge transfer upon contact between a polymer film and a metal probe, as evidenced by measurement of contact current, is found to increase as a function of film thickness. Current measurements reach a saturation value for films approximately 400 Å thick. Additionally, contact charge measurements are found to be highly dependent on specific processing conditions which allow control over the surface roughness at the polymer/silicon interface for films in the same thickness range (<400 Å).

EXPERIMENTAL DETAILS

Contact-Separation Technique

Most of the work in the area of contact electrification has been concerned with conventional polymers several microns thick. Our work involves thin plasma polymerized films in the thickness range 100 to 600 Å. Plasma polymerized methane films of varying thickness are prepared by keeping system parameters constant and varying the deposition time. All samples are held under vacuum for 24 h after completion of the deposition before subsequent storage in a nitrogen atmosphere. A systematic study concerning charge measurements as a function of time after deposition has given us a great deal of information about the aging effect for these polymer films.¹² To minimize effects due to aging, all samples are tested at an age of 90 days.

The equipment used for this measurement includes a Keithley 617 programmable digital electrometer and a Fluke 8842A multimeter under program control. The electrometer is used to measure the extremely small currents which occur during contact and subsequent separation between a metal and an insulator. The output of the electrometer is connected to the input of the multimeter in order to take advantage of the multimeter's higher data output rate. The contact-separation measurement apparatus and principle of operation are described in detail elsewhere^{13,14} Current in the picoampere range is observed during contact and subsequent separation between the polymer film and a metal probe. The current reaches a peak value and then dies out. The total charge transferred can be calculated by integrating the current vs. time curve. A similar measurement is then made by measuring the current when the metal and polymer film are separated. The measurement sequence is repeated for a total of 10 times. With our instrumentation, after several repeated measurements, the peak current,

or maximum current, readings settle into a small range of values. This usually has occurred by the time the fifth test has taken place.¹⁴ Contact charge values are compared to peak contact current values for a variety of films to determine the feasibility of using peak current values to characterize the films under test. The resulting curves are essentially the same. Because the peak height is a single value which is quickly and easily determined, and because this value varies with the amount of charge transferred, peak current data, instead of charge data, are used to characterize the charge transfer upon metal-polymer contact. The theory which justifies using peak heights instead of calculated charge is given elsewhere.¹³

Plasma Polymerization of Methane

Plasma deposition of organic coatings has become an important technique for the deposition of amorphous, pinhole-free, highly crosslinked, conformal thin films of superior physical, chemical, and mechanical properties. A schematic representation of the vacuum system that is used to deposit the polymer films is shown in Figure 1. The vacuum deposition chamber is a bell jar with parallel internal electrodes. The electrodes are capacitively coupled and permanent magnets are arranged on the back side of each electrode in a circular configuration. The effect of the magnetic field is to confine electrons near the electrode and increase the chance for a dissociative collision with a molecule. Without a magnetic field, electrons essentially travel in a straight path between electrodes. The presence of the magnetic field causes the electrons to travel in a spiral path, decreasing the effective mean free path, resulting in a higher effective electron concentration within the discharge.¹⁵ The magnetic field makes it possible to create and sustain a plasma at a lower pressure.

The monomer gas, methane, is fed in through a tube whose outlet is above the electrodes. Mass flow controllers and pressure controllers are used to allow reproducible system conditions. Power is supplied to the electrodes by an Advanced Energy 40 kHz ac power supply. Silicon substrates, *p*-type, <100> oriented, are mounted with double sided conducting copper foil tape on a circular disk that rotates in the interelectrode space. It is well known that rotation of the substrate through the glow improves the uniformity and reproducibility of the film.¹⁶ Rotation of the substrates in the interelectrode space also makes it possible to fabricate multiple samples with the same film thickness in a single deposition. This

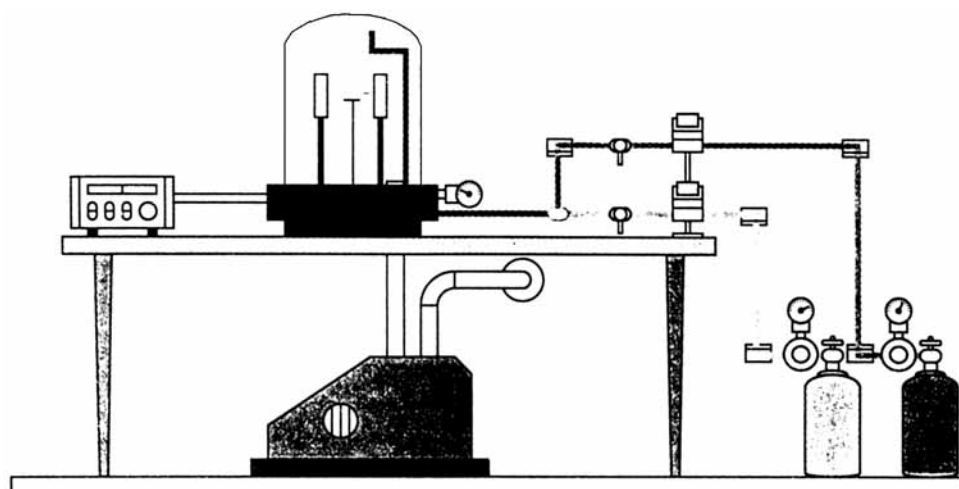


Figure 1 Schematic of vacuum system for plasma polymerization of methane.

results in practically identical samples with minimal variation in film composition, and is useful in comparison studies.

Deposition rates of approximately 90–100 Å/minute are achieved with the following system parameters: monomer flow rate of 1.65 sccm; system pressure of 50 mTorr; and a power setting of 50 watts. The thickness of the resulting plasma polymerized methane film is controlled by holding system parameters constant and varying the deposition time as previously mentioned. Ellipsometry measurements over the entire film are used to evaluate film thickness. After deposition, samples are removed from the vacuum system and placed in a nitrogen chamber for storage in a controlled environment prior to testing.

FILM UNIFORMITY

Before conducting experimental studies with the objective of determining the effect of film thickness on contact electrification, it is necessary to ensure the deposited films are uniform in thickness. For magnetically enhanced plasma deposition systems, film thickness and index of refraction vary across the electrode.¹⁷ A minimum deposition rate occurs at the center of the electrode and increases with radial distance from the center and reaches a maximum rate at a few centimeters from the electrode center axis.¹⁸ This variation in deposition rate is apparent when observing the pattern on the electrode after the deposition is complete. However, polymers formed by plasma polymerization deposit uniformly across a moving substrate positioned midway between capacitively coupled electrodes.^{16,19}

In fact this has been proven necessary to ensure film uniformity for large substrates.^{15,17}

Characterization of the polymer film thickness is done ellipsometrically. A Gaertner model L117 ellipsometer with a helium neon laser source ($\lambda = 6328\text{\AA}$) is used for this purpose. Profilometry measurements are compared to measurements obtained with ellipsometric techniques. A plastic scribing tool inserted in a semiconductor wafer scribing machine is used to scribe a smooth line through the polymer film without scratching the silicon substrate.²⁰ This produces a sharp step in the film which can be traced using a profilometer (Tencor Alpha-Step 200). Thickness measurements resulting from profilometer traces are in excellent agreement with ellipsometry measurements for plasma polymerized methane films.¹³

A total of 25 data points (5×5 array) are taken across the surface of the sample in the area involved in the contact to the metal probe. Interpolation software is used to generate points between measured data points for smoothing and increased resolution. The data are illustrated three-dimensionally in Figure 2 and represent data for a sample allowed to rotate through the plasma zone as opposed to the case of a stationary substrate. The film is very uniform in thickness with a small well in the center of the sample. From the ellipsometry measurements, an average film thickness and index of refraction are calculated, along with a maximum, minimum, and standard deviation for four different samples. The results are shown in Table I. The variable (δ) is defined as the difference between the maximum and minimum measurements for a particular sample and is indicative of the deviation in film thickness across a sample. Figure 3 represents the variation

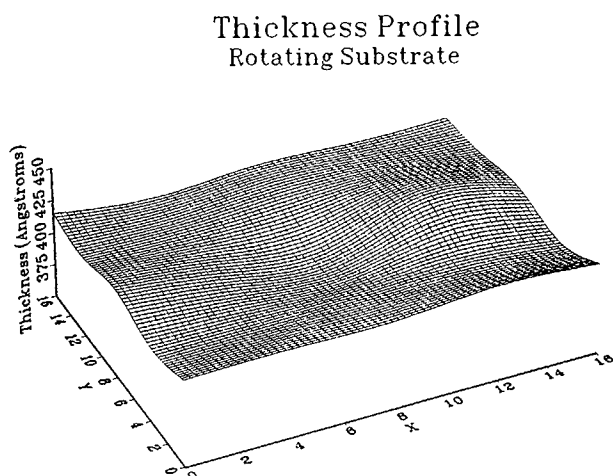


Figure 2 Thickness profile for rotating substrates.

in film thickness (high-low-average) for rotating and stationary substrates. This figure clearly illustrates why rotating substrates are necessary for this work.

Experimental results from reproducibility studies confirm the fact that reproducible charge measurements can be obtained when the deposition process is carefully controlled. Reproducible charge measurements have been confirmed for each of the following cases: sample to sample from the same deposition; place to place on one sample; and sample to sample from different depositions.^{12,13} Establishing a reproducible deposition environment is critical to depositing reproducible films and is crucial when films with different treatments are being compared. Film thicknesses of approximately 600 Å were used in reproducibility studies, however, reproducible charge measurements have been observed in our work on 100 Å films on metal substrates.^{11,21}

High-Low-Average Plot
Rotating and Stationary Substrates

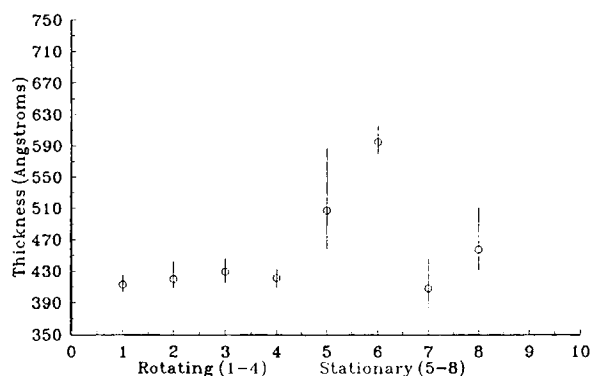


Figure 3 High-Low-Average plot of film thickness for rotating and stationary substrates.

THICKNESS OF CHARGE LAYER

The objective of this work is to investigate the effect of film thickness on contact electrification and to use this information to speculate on the relative thickness of the charged layer. In previous experimental studies performed in our laboratory,¹³ film thickness is kept constant to determine the effect of various conditions on virtually identical films. The individual studies are concerned with charging characteristics of the films over time, postdeposition treatments, storage in different atmospheres, and reproducibility in charge measurements. Results of contact electrification experiments on a variety of polymers formed by plasma polymerization indicate that the amount of charge exchange upon metal-insulator contact varies with film thickness.¹¹ The experiment described in this paper is designed to evaluate the relationship between film thickness and

Table I Film Thickness (Å) and Index of Refraction Data for Rotating Substrates

Sample #	Film Thickness (Å)				δ (Max - Min)
	Mean	Maximum	Minimum	Standard Deviation	
1	413.3	426	403	5.42	23
2	420.3	443	408	8.07	35
3	429.4	447	415	8.66	32
4	421.4	432	409	6.44	23
Sample #	Index of Refraction				δ (Max - Min)
	Mean	Maximum	Minimum	Standard Deviation	
1	1.589	1.618	1.557	0.015	0.061
2	1.637	1.663	1.601	0.015	0.062
3	1.609	1.662	1.579	0.020	0.083
4	1.586	1.653	1.603	0.014	0.050

contact electrification for plasma polymerized methane films.

There has been considerable disagreement among various investigators as to whether contact electrification is due to a very thin layer of charge in surface states or the other extreme, to charge extending several hundred angstroms into the bulk. It is commonly believed that states deep in the bulk of an insulator are unlikely to play any part in contact electrification, because they are inaccessible to electrons from the contacting metal. However, bulk states which happen to lie very close to the surface can communicate with a contacting metal because electrons can tunnel short distances into the insulator.^{3,5} One of the advantages of the contact-separation measurement technique is that ultrathin films (~ 100 Å) can be evaluated. This information aids in determination of the influence of the insulator/substrate interface on charge exchange in metal-insulator contacts.

There is experimental evidence that contact electrification is a surface effect. A measurement of internal photoinjection from a metal to the polymer conduction band has been carried out by Mizutani et al.⁶ The barrier height was determined for Cu and Al contacts with polyethylene terephthalate (PET). The difference in barrier height between Cu and Al contacts was found to be much smaller than the work function difference of the metals. The existence of surface states was inferred and their density estimated with simple models. Exposure to oxygen strongly affected the measured barrier height, suggesting that adsorbed molecules could act as electron traps. Similarly, Hays has shown that exposure to ozone increases the charging of polyethylene by mercury, presumably because of new chemical groups formed at the polymer surface.² Hays has also shown that ultraviolet (UV) radiation induced changes, localized within 8 Å of the surface, can determine the magnitude of the charge transfer in mercury-polystyrene contacts.²² Kittaka and Murata found that polyethylene and polypropylene, which normally charge negatively when contacted by metals, will charge positively if exposed to high energy UV light before contact.^{7,23} Pre-exposure to UV results in electrons being transferred from deep occupied levels into previously unoccupied shallow levels. The polymer charges positively because the electrons excited into the higher states of the polymer transfer to the metal when contact is established.

Homewood obtained a value for charge penetration depth of approximately 4–8 Å in polymethylmethacrylate (PMMA) contacted by mercury.⁹

Controlled surface enrichment of a polyblend by the addition of increasing quantities of a fluoropolymer has shown that charging upon contact with other polymers is related to composition to a depth of about 15 Å, but the charging upon contact with metals depends on composition to a depth which is intermediate between surface and bulk.²⁴ It has been postulated that the charge penetration depth into a polymer is greater when contact is made with metals than with other polymers, though the magnitudes of the charges are comparable.

Nordhage and Bäckström²⁵ used externally applied fields to measure the depth of charge distribution. They found the charged layer to be approximately 400 Å thick. This is too high to correspond to surface states, which led them to conclude that charge cannot be confined to states on the insulator surface but must penetrate approximately 400 Å into the bulk of the insulator. Davies also found charge penetration depths ranged from 100 to 500 Å by conventional field mill techniques.¹ Fabish et al. propose the thickness of the charge layer must be of the order of 2–4 microns because of deviations from theoretical predictions in charge transfer between metal and polystyrene when the sample thickness is less than a few microns.^{4,26} Lowell presents experimental evidence indicating that it is not possible to estimate the depth of penetration of charge from observations of the effect of an electric field on contact electrification.⁸ It is obvious the variety in experimental findings related to determination of charge penetration depth.

EXPERIMENTAL RESULTS

Variation in Film Thickness

A typical contact sequence for plasma polymerized methane (125 Å) on *p*-type silicon contacted by a gold probe is shown in Figure 4. A commonly observed phenomenon is the accumulation of charge on the surface of an insulator following repeated contact with another material.^{3–5,27} Usually the rate of increase of the charge decreases as contacts are repeated and, after many contacts, the charge may appear to saturate. This same phenomenon is observed in our experiments and for this reason, the last five current values are averaged to characterize a given film. The reasons for charge accumulation after repeated contacts to an insulator with a solid metal are not fully understood. Several explanations have been suggested but each seems applicable only to a specific insulator or experimental technique.

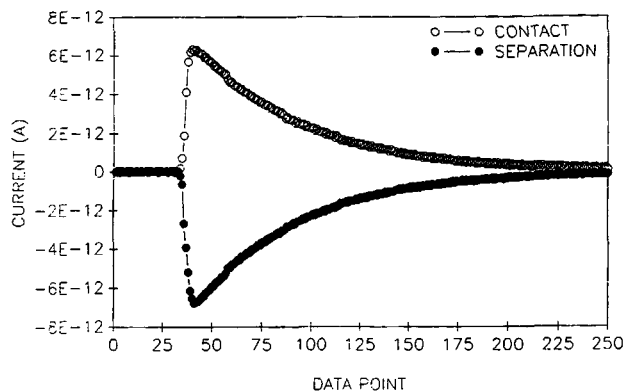


Figure 4 Contact-separation peaks for plasma polymerized methane on *p*-type silicon.

Figure 5 is a graph of average peak contact current vs. film thickness for films contacted by a gold probe. An increase in average peak contact current is observed for increasing film thickness in the range of 150–400 Å. Increased contact charging has also been observed by Fabish et al. for increasing film thickness of polystyrene films contacted by indium.⁴ Plasma polymerized methane films exhibit a steady increase in average peak contact current as a function of film thickness. Increasing film thickness greater than approximately 375 Å has little effect on the contact current measurement indicating, perhaps, that there is a limiting film thickness beyond which charge penetration depth does not increase.

This figure also suggests that the metal-insulator contact could be influenced by the insulator/substrate interface up to a limiting film thickness. For

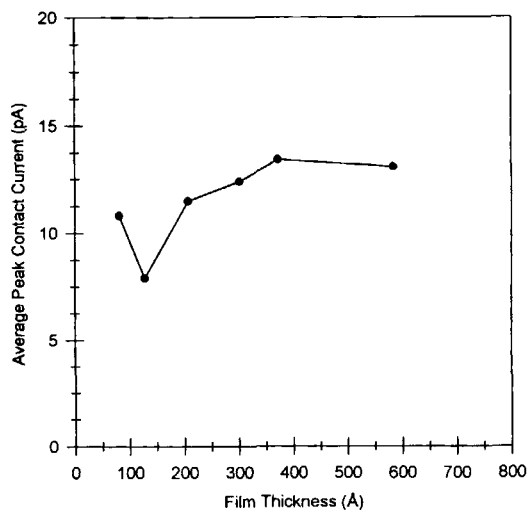


Figure 5 Average peak contact current versus film thickness for a gold probe.

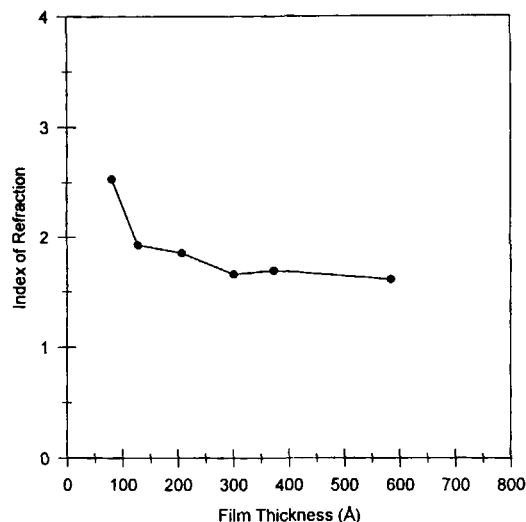


Figure 6 Index of refraction vs. film thickness.

film thicknesses below 100 Å, an increase in average peak contact current with decreasing thickness is observed. One possible explanation for this observation is that there is a difference in the composition of ultrathin films. The index of refraction for each film is determined and is shown graphically in Figure 6. Polymer films less than 100 Å thick do exhibit a higher index of refraction than that of thicker films. The same trend is illustrated in Figure 7, which shows average peak contact current vs. film thickness for films contacted by an alternate metal probe made of brass. One difference to note is that the average peak contact current for ultrathin films does not show a marked increase compared to slightly thicker films.

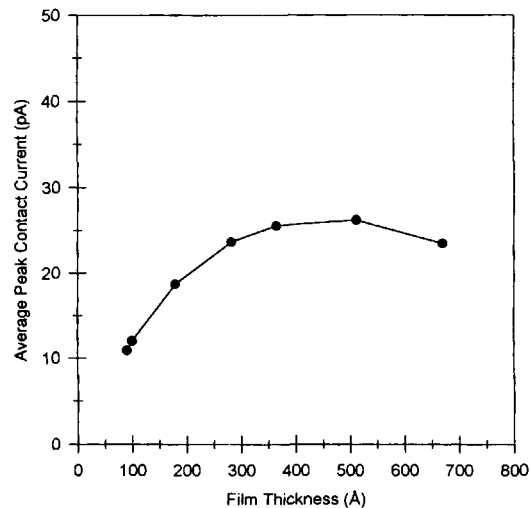


Figure 7 Average peak contact current vs. film thickness for a brass probe.

Variation in Substrate Treatment

Because of previous observations in our laboratories in regard to the interaction of the substrate in contact electrification experiments for thin polymer films, the objective of another set of experiments is to alter the substrate previous to plasma deposition and evaluate the effect of the polymer/substrate interface on charge measurements. It is well known that variations in processing may strongly influence properties of the interface between a silicon dioxide film and the silicon substrate. Two processing variations that consist of high temperature annealing and substrate polishing are used to purposely change the silicon surface before deposition of plasma polymerized methane films.

An important processing technique to improve the quality of the interface between silicon and thermally grown silicon dioxide is the postoxidation anneal (POA). Annealing in an inert atmosphere is a standard procedure for minimizing the fixed oxide charge and interface state density. The annealing technique is used on chemically clean silicon substrates with only a native oxide layer present. Annealing of the substrate is done at 1000°C in a nitrogen atmosphere for 30 min to improve the electrical properties of the interface previous to plasma deposition. Silicon substrates without the high temperature anneal are also used as control samples for comparison.

In addition to the anneal, a substrate polishing procedure is employed to purposely roughen the surface and offer an increased surface state density. A fine polishing abrasive (0.3 microns) is used for this purpose. An aluminum contact is formed on the back side of each substrate before plasma deposition. A thin plasma polymerized methane film (≈ 100 Å) is deposited on each type of substrate. Contact-separation tests are performed and Figure 8 shows peak contact current vs. number of contacts to a brass probe for the three different substrates. If contact charging is caused by electron transfer from or to interface states, the charging tendency of thin films will be changed by substrate treatments. It is apparent from Figure 8 that there is an inverse relationship between contact current for plasma polymerized methane in contact with brass and surface state density at the insulator/substrate interface.

One way to view the relationship between contact current and substrate treatment is in the context of a triboelectric series. A triboelectric series is an arrangement of materials which relates their charging behavior. The relative polarity of charge acquired on contact between materials in the series is pre-

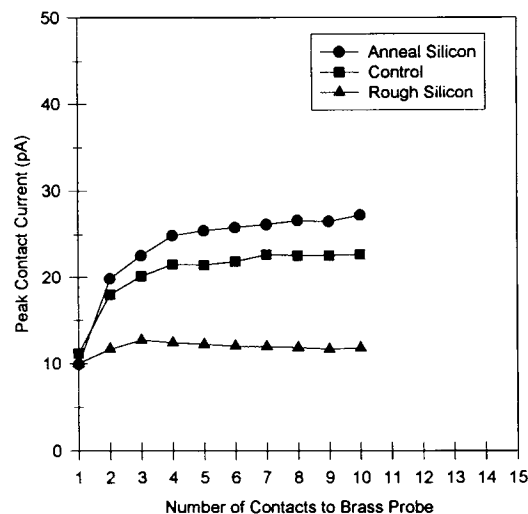


Figure 8 Peak contact current vs. number of contacts to brass for plasma polymerized methane (100 Å) on annealed, control, and rough silicon substrates.

dictable by its location. By polishing the substrate with an abrasive powder, electronic states are introduced, creating a negatively charged surface which corresponds to the bottom of a triboelectric series defined in such a way as to place negatively charged materials at the bottom. On the other hand, annealing the substrate decreases the density of states and can be associated with positive charging, or placement at the top of the series. The results from this experiment show that when a substrate is treated in such a way as to reduce the density of interface states, the most positively charged insulator results, and increasing the interface state density allows for movement down the series toward a more negatively charged insulator.

This study is extended to include films of varying thickness. Each treated substrate is coated with plasma polymerized methane films of varying thickness. The substrates treated with the polishing procedure are eliminated due to difficulties associated with the lack of reproducibility in this processing procedure. Contact-separation measurements are performed on each type of substrate (annealed and control). Peak contact current for two samples of each substrate type contacted by a gold probe is shown in Figures 9–13. Each figure corresponds to a different film thickness. From this series of graphs, the effect of the substrate treatment on contact current can be observed in relation to film thickness. The polymer films deposited on annealed substrates charge more positively than the control substrates until a limiting thickness of approximately 300–375 Å is reached. Beyond that thickness, the substrate

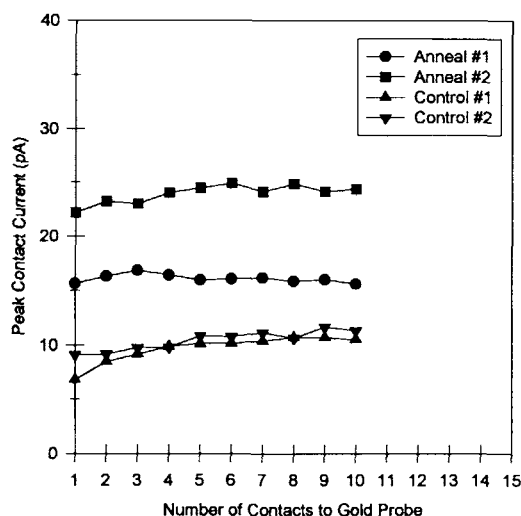


Figure 9 Peak contact current vs. number of contacts to gold for plasma polymerized methane (80 Å) on substrates with processing variations.

treatment has no substantial effect on peak contact current.

A final experiment concerning plasma polymerized methane films involves deposition of a variety of metals on silicon substrates to again purposely alter the substrate previous to deposition of the insulating films. For this study, platinum, aluminum, gold, and silver are deposited on silicon substrates. Each silicon sample is first coated with a thick layer of aluminum (≈ 5000 Å) by thermal evaporation. Aluminum of the same thickness is then evaporated on the back side for good ohmic contact. DC sput-

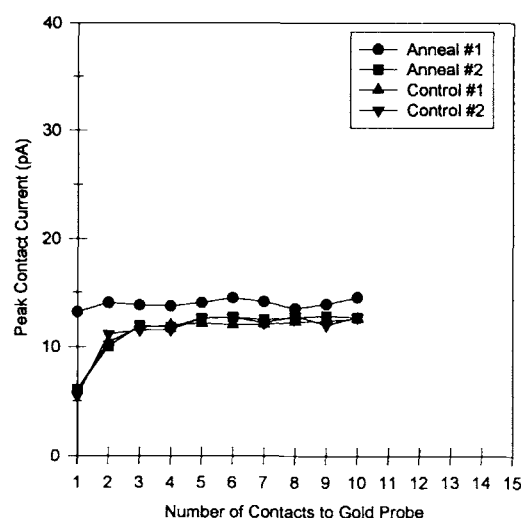


Figure 11 Peak contact current vs. number of contacts to gold for plasma polymerized methane (300 Å) on substrates with processing variations.

tering of high purity metal targets is used to provide uniform coatings (≈ 500 Å) of platinum, gold, and silver with high electrical conductivity on top of the aluminum coated silicon. Evaporated aluminum with no additional sputtered metal comprises the fourth substrate type. Plasma polymerized methane films approximately 100 Å thick are then deposited on the four types of metal coated silicon substrates.

Contact-separation measurements are performed to determine the effect of each of the metal substrates on contact current measurements. Peak contact current for thin polymer films on a variety

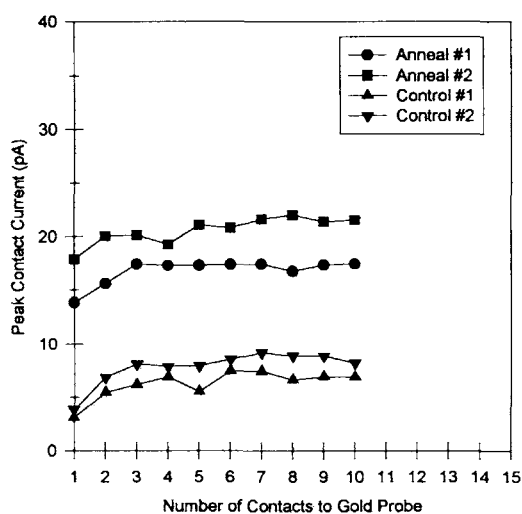


Figure 10 Peak contact current vs. number of contacts to gold for plasma polymerized methane (130 Å) on substrates with processing variations.

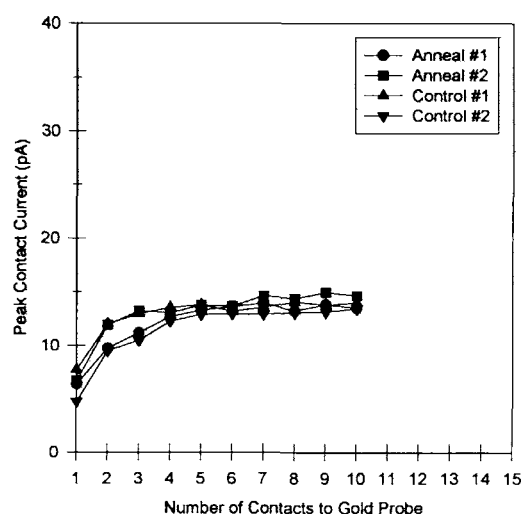


Figure 12 Peak contact current vs. number of contacts to gold for plasma polymerized methane (375 Å) on substrates with processing variations.

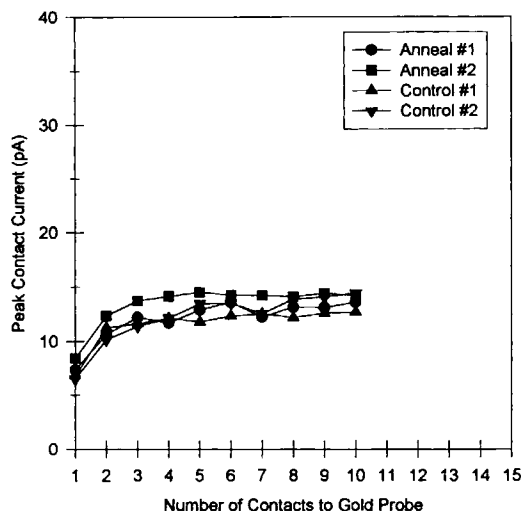


Figure 13 Peak contact current vs. number of contacts to gold for plasma polymerized methane (585 Å) on substrates with processing variations.

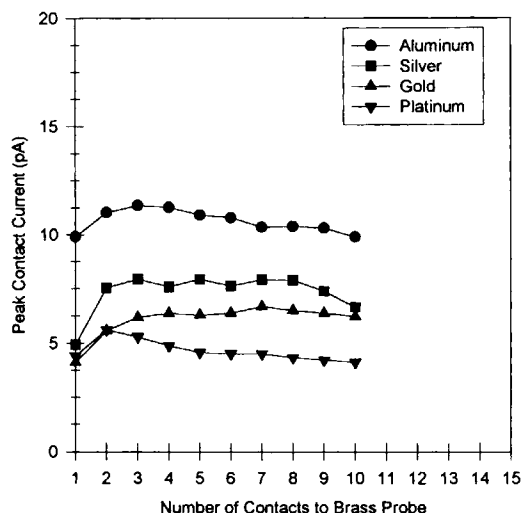


Figure 14 Peak contact current vs. number of contacts to brass for plasma polymerized methane (100 Å) on substrates with various metal substrates.

of metal substrates as measured upon contact with a brass probe is shown in Figure 14. Peak contact current varies depending on the metal substrate chosen because of the difference in work function for each of the metals. Charge exchange takes place between the insulating film and its metal substrate. Work function values for the metals used in this experiment are 4.1, 4.3, 4.75, and 5.3 eV for aluminum, silver, gold, and platinum, respectively.^{28,29} Average peak contact current vs. work function (eV) of the substrate metal is shown in Figure 15. There appears to be a linear relationship between peak contact current and work function of the substrate metal. This is an important observation because the dependence of contact current on substrate metal work function gives evidence of electron transfer upon contact between plasma polymerized methane films and a metal probe. Electron transfer is generally believed to be the mechanism for contact electrification of polymers in contact with metals.

SUMMARY

The main objective of this set of experiments is to evaluate polymer films of varying thickness and determine the relationship between contact electrification characteristics and film thickness. In addition to film thickness, substrate treatments are shown to affect contact electrification measurements for the polymeric materials studied. Experimental results show that either true surface states or bulk states which are sufficiently close to the interface

play an important role in contact electrification. States available at the insulator/substrate interface may communicate with the contacting metal by tunneling or some other mechanism. The insulator/substrate interface has been shown to have a strong effect on measured contact current. The contact-separation measurement technique is an experimental method which makes it possible to determine charge penetration depth due, in part, to the capability of the instrument in making charge measurements on thin insulating polymer films. Experimental methods for determining the depth of charge

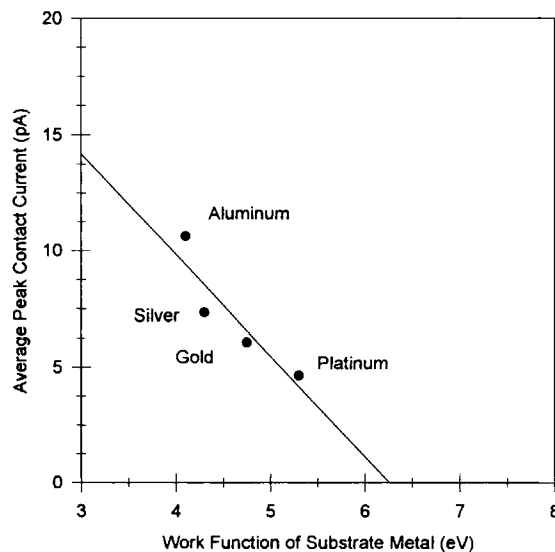


Figure 15 Average peak contact current vs. work function of metal substrate.

penetration are either not very reliable or are of limited applicability, and more research is needed in regard to this important aspect of contact electrification.

REFERENCES

1. D. K. Davies, *Adv. Static Electrification*, **1**, 10 (1970).
2. D. A. Hays, *J. Chem. Phys.*, **61**, 1455 (1974).
3. J. Lowell, *J. Phys. D: Appl. Phys.*, **9**, 1571 (1976).
4. T. J. Fabish, H. M. Saltsburg, and M. L. Hair, *J. Appl. Phys.*, **47**, 930 (1976).
5. T. J. Fabish, H. M. Saltsburg, and M. L. Hair, *J. Appl. Phys.*, **47**, 940 (1976).
6. T. Mizutani, Y. Takai, T. Osawa, and M. Ieda, *J. Phys. D: Appl. Phys.*, **9**, 2253 (1976).
7. S. Kittaka and Y. Murata, *Jpn. J. Appl. Phys.*, **18**, 515 (1979).
8. J. Lowell, *J. Phys. D: Appl. Phys.*, **14**, 1513 (1981).
9. K. P. Homewood, *J. Phys. D: Appl. Phys.*, **17**, 1255 (1984).
10. J. Lowell and A. C. Rose-Innes, *Adv. Phys.*, **29**, 947 (1980).
11. E. M. Charlson, E. J. Charlson, S. Burkett, and H. K. Yasuda, *J. Appl. Polym. Sci.: Appl. Polym. Symp.*, **46**, 109 (1990).
12. S. L. Burkett, E. M. Charlson, E. J. Charlson, and H. K. Yasuda, in *Proc. Conference on Electrical Insulation and Dielectric Phen*, British Columbia, 391 (1992).
13. S. L. Burkett, *Electrical Characterization of Polymer and Dielectric Structures*, Ph.D. Dissertation, University of Missouri, 1992.
14. E. M. Charlson, E. J. Charlson, S. Burkett, and H. K. Yasuda, *IEEE Trans. Elec. Insul.*, **EI-27**, 1144 (1992).
15. H. Yasuda, *Plasma Polymerization*, Academic Press, Orlando, 1985.
16. A. K. Sharma, Y. Matsuzawa, and H. Yasuda, *J. Appl. Polym. Sci.: Appl. Polym. Symp.*, **38**, 225 (1984).
17. M. F. Leahy and G. Kaganowicz, *Solid State Technology*, 99 (1987).
18. N. Morosoff, W. Newton, and H. Yasuda, *J. Vac. Sci. Technol.*, **15**, 1815 (1978).
19. N. Inagaki and H. Yasuda, *J. Appl. Polymer Sci.*, **26**, 3425 (1981).
20. E. J. Charlson, E. M. Charlson, A. K. Sharma, and H. K. Yasuda, *J. Appl. Polymer Sci.: Appl. Polym. Symp.*, **38**, 137 (1984).
21. H. Yasuda, E. J. Charlson, E. M. Charlson, T. Yasuda, M. Miyama, and T. Okuno, *Langmuir*, **7**, 2394 (1991).
22. D. A. Hays, *Inst. Phys. Conf. Ser.*, **48**, 265 (1979).
23. Y. Murata, *Jpn. J. Appl. Phys.*, **18**, 1 (1979).
24. M. W. Williams, *J. Macromol. Sci.-Rev. Macromol. Chem.*, **14**, 251 (1976).
25. F. Nordhage and G. Bäckström, *Inst. Phys. Conf. Ser.*, **27**, 84 (1975).
26. T. J. Fabish and C. B. Duke, *J. Appl. Phys.*, **48**, 4256 (1977).
27. W. R. Harper, *Contact and Frictional Electrification*, Oxford University Press, London, 1967.
28. R. S. Muller and T. I. Kamins, *Device Electronics for Integrated Circuits*, John Wiley & Sons, New York, 1977.
29. N. W. Ashcroft and N. D. Mermin, *Solid State Physics*, Holt, Rineheart, and Winston, Philadelphia, 1976.

Received December 11, 1995

Accepted February 8, 1996