Charge erasure analysis on the nanoscale using Kelvin probe force microscopy

Shi-quan Lin and Tian-min Shao

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Charge erasure analysis on the nanoscale using Kelvin probe force microscopy

Shi-quan Lin and Tian-min Shao[a]
State Key Laboratory of Tribology, Tsinghua University, Beijing 100084, China

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The charge pattern produced by atomic force microscopy on an insulating surface can be detected on the nanoscale using Kelvin probe force microscopy. Recent applications of charge patterns include data storage, nano-xerography, and charge writing. At present, ongoing development of this technology is being restricted by a poor understanding of the charge modification and erasure mechanisms. In this study, modification and erasure of charge patterns are achieved by applying oppositely polarized pulses to an insulating surface. The effects of the oppositely polarized pulse height and width on the charge erasure behavior are examined, and the charge injection and erasure processes are compared. Hence, it is demonstrated that the charges on the patterned surface can be neutralized by adjusting the height and width of the oppositely polarized pulse appropriately. In addition, charge injection and erasure mechanisms are proposed. It is suggested that application of an oppositely polarized pulse to the insulating surface causes injection of opposite charges into the surface and removal of the initial charges, both of which occur simultaneously. The findings of this work provide a means of achieving data re-storage or data modification, for which charge spot erasure is essential. In addition, the findings may have general implications for the development of nano-xerography, charge writing, nano-lithography, etc. *© 2017 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).* [http://dx.doi.org/10.1063/1.4989568]

I. INTRODUCTION

Charge injection technology has been used in data storage,[1,2] nano-xerography,[3] charge writing,[4] etc. To develop this technology and its various applications, the majority of investigators have focused on investigating the charge injection process.[5–10] In this process, a charge can be injected into an insulating surface through application of a pulsed bias between the conductive tip of an atomic force microscope (AFM) and the insulating surface when they are in contact. This injected charge can be measured using Kelvin probe force microscopy (KPFM).[11,12] In addition, erasure of the resultant charge pattern is possible; however, understanding of the charge erasure mechanism is poor, and this lack of knowledge is becoming a significant hindrance to the ongoing development of charge injection applications. For example, charge spot erasure is essential for data re-storage or data modification in data storage applications.[2] Further, in nano-xerography, a picture is drawn by injecting a charge into a surface, and it is possible to rectify errors by removing this charge. Moreover, it may be also possible to prevent charge accumulation and disruptive discharge in microelectronics, which can damage these devices, by erasing the surface charge in a timely manner.[13,14]

The pioneering works on charge erasure have demonstrated that a nanoscale charge pattern on an insulating surface can be erased via rubbing or through contact with a conductive tip, or by applying a pulse of opposite polarity to the charge pattern.[2,15] However, although surface charge erasure has been achieved, detailed understanding of the charge erasure process is lacking and many questions remain unanswered. For example, it is possible for the oppositely polarized charge used to erase

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[a] Electronic mail: shaotm@tsinghua.edu.cn.

the surface charge to be over-injected into the surface, if the pulse height is too large. Thus, the ability to determine the appropriate oppositely polarized pulse necessary to remove a given surface charge pattern is important for charge erasure. Unfortunately, the effects of the oppositely polarized pulse height and width on the charge erasure have not been investigated to date. Another aspect that is rarely considered is the differences between the charge injection and erasure processes. Knowledge of the mechanisms behind these processes is also important for data storage, so as to prevent disruptive discharge, etc., as the charge injection and erasure processes must be repeated at some point in a data storage device. Thus, it is necessary to ensure that the charge erasure process does not affect the next charge injection process.

In this paper, the charge injection and erasure processes on an insulating surface are studied using AFM/KPFM. Different numbers of charges are produced on the insulating surface through application of various pulse heights on a conductive tip, and appropriate pulses of opposite polarity are then chosen to neutralize these surface charge patterns. The charge injection and erasure processes are compared and charge injection and erasure mechanisms are proposed.

II. EXPERIMENTAL PROCEDURE

Dimension Icon (Bruker, USA) AFM/KPFM equipment was used to produce the charge patterns examined in this study, and to examine the charge erasure behavior on the nanoscale. The AFM and KPFM mechanisms have been described elsewhere.[11,16] As the sample, SiN_x film of 100-nm thickness deposited on a highly doped silicon wafer via plasma enhanced chemical vapor deposition (PEVCD) was used.

A pulse was applied to a conductive tip (NSC 18; MikroMasch, USA; coating: Au/Cr; tip radius: 25 nm; spring constant: 3 N/m) placed in contact with the SiN_x film in order to inject and erase the surface charge. Fig. 1 shows a schematic of the experimental procedures. Under the AFM contact mode, the tip was controlled to make contact with the SiN_x surface on a point-by-point basis as shown in Fig. 1(a), with a 50-nN contact force. The point positions are shown in Fig. 1(c). When the tip was in contact with the surface at the contact points, pulses were applied.

The KPFM mode was used to measure the resultant changes in the contact-region surface potential, as shown in Fig. 1(b). For the charge erasure experiments, charges were first injected into the surface by applying pulses with the same height and width to all points. Then, pulses of opposite polarity and with various heights and widths were applied to the tip at different contact points, so as to remove the existing charges. By measuring the surface potentials at the different contact points following the erasure process, the most appropriate pulse for charge erasure of the given charge

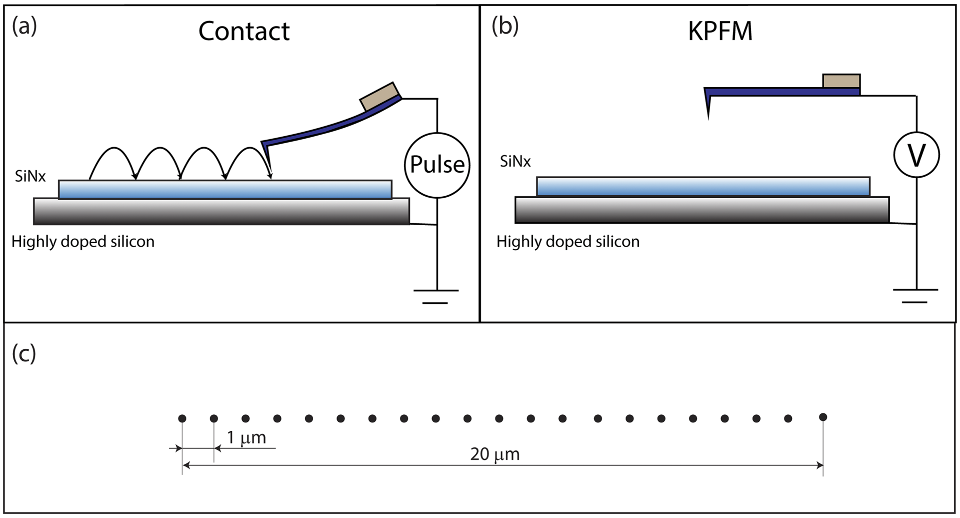

FIG. 1. Schematics of charge injection and erasure experiments. (a) The tip was controlled to make contact with the SiN_x surface in a point-by-point manner. (b) The KPFM mode was used to measure the surface charge. (c) Contact-point arrangement.

patterns could be determined. All the experiments were completed under atmospheric conditions, at 25 degrees Celsius and 35% relative humidity.

III. RESULTS

A. Charge injection

In the charge injection experiment, the pulse heights used to inject the surface charges were varied from -12 to +12 V uniformly and point-by-point in 1.2-V intervals. The pulse width was set to 1 s. Fig. 2(a) shows the surface potentials after the charge injection. In addition, the upper part of Fig. 2(b) shows the surface potential as a function of position, as extracted from the result shown in Fig. 2(a). The relationship between the peak surface potentials of the contact points and the pulse height is shown in the bottom image of Fig. 2(b). From the results shown in Fig. 2, it is noteworthy that the peak surface potential increased with pulse height, and that the charge pattern was asymmetric between positive and negative pulses. Further, these results indicate that the SiNx film was inclined to acquire a negative charge. Such charge-injection asymmetry has been reported in previous studies.[15,17,18]

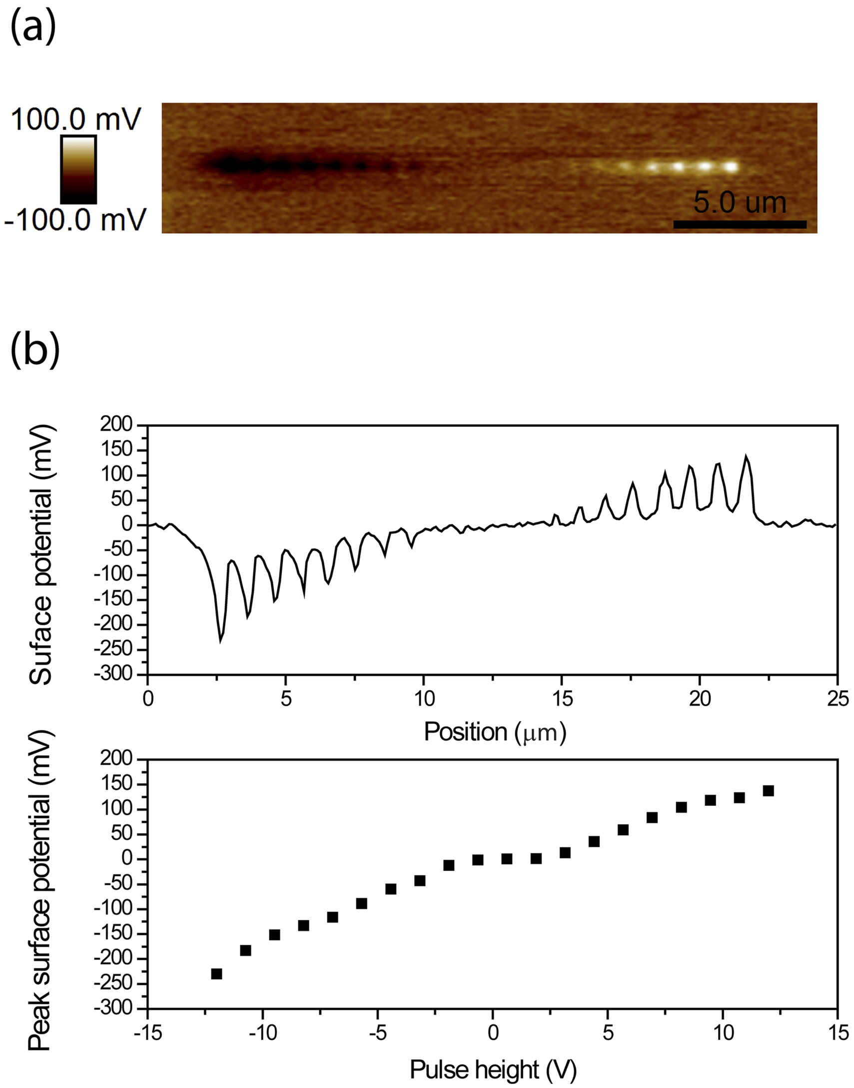

FIG. 2. Effect of pulse height on charge injection. (a) Surface potentials of charge points following contact with conductive tip, where the pulse was varied from -12 to +12 V uniformly in 1.2-V intervals. The pulse width was 1 s. (b) Surface potential values extracted from (a): (top) Surface potential as function of position and (bottom) peak surface potential as function of pulse height.

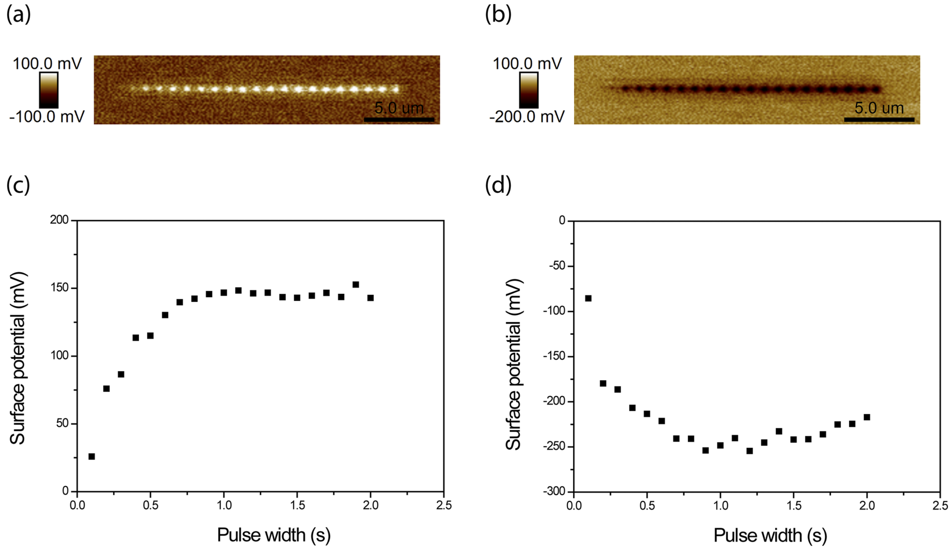

FIG. 3. Effect of pulse width on charge injection. Surface potentials of charge points following contact with conductive tip with (a) +12 and (b) −12 V pulse heights, where the pulse width was varied uniformly from 0.1 to 2.1 s in 0.1-s intervals. (c, d) Surface potential values as functions of pulse width extracted from (a) and (b), respectively.

The effect of the pulse width on the charge transfer was also tested, and the results are shown in Fig. 3. In this experiment, the pulse widths were varied from 0.1 to 2.1 s uniformly and point-by-point in 0.1-s intervals, and the pulse heights were (a, c) +12 and (b, d) −12 V. For both the positive

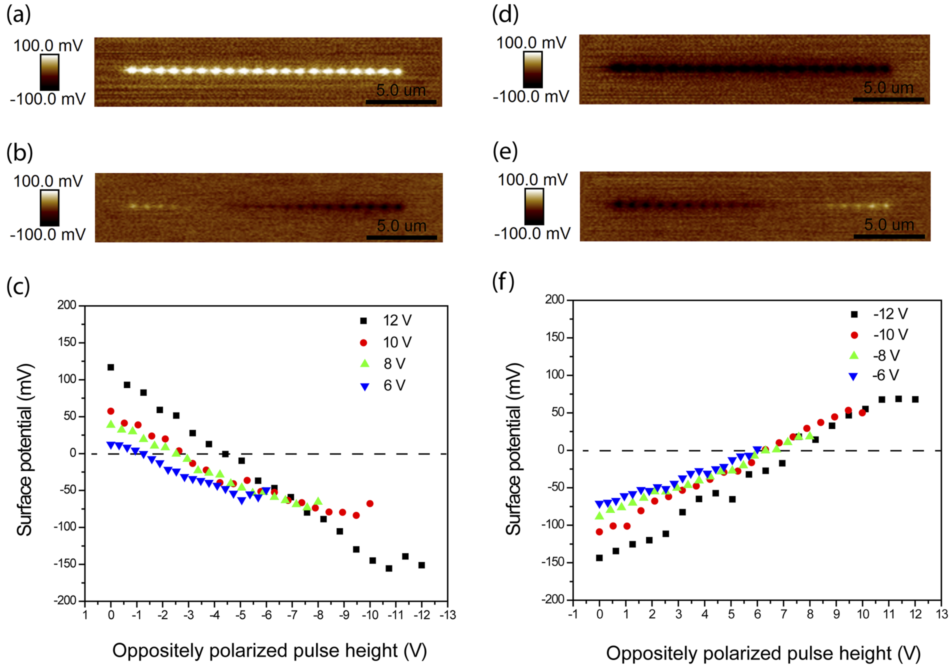

FIG. 4. Effect of oppositely polarized pulse height on charge erasure. (a) Surface potentials of contact points at which charges were injected using identical pulses (height: +12 V; width: 1 s). (b) Surface potentials of contact points following application of oppositely polarized pulses with heights varying from 0 to −12 V in −0.6-V intervals and with widths of 1 s to different points for charge erasure. (c) Surface potentials after charge erasure process, for initially injected charges of 12 (black), 10 (red), 8 (green), and 6 V (blue). (d) Surface potentials of contact points at which charges were injected using identical pulses (height: −12 V; width: 1 s). (e) Surface potentials of contact points following application of oppositely polarized pulses with heights varying from 0 to +12 V in 0.6-V intervals and with widths of 1 s to different points for charge erasure. (f) Surface potentials after charge erasure process, for initially injected charges of −12 (black), −10 (red), −8 (green), and −6 V (blue).

and negative injection pulses, the changes in the surface potential were found to increase exponentially with pulse width, reaching saturation for a pulse width larger than 1 s.

B. Charge erasure

The effect of the oppositely polarized pulse height on the charge erasure was examined, as shown in Fig. 4. Fig. 4(a) shows the surface potentials of an SiN_x specimen on which charges were injected using identical pulses (height: +12 V; width: 1 s). Then, oppositely polarized pulses with heights in the 0 to −12-V range in −0.6-V intervals and with widths of 1 s were applied to these points for charge erasure; the results are shown in Fig. 4(b). In addition, different pulse heights were used for surface charge injection on another SiN_x specimen. Oppositely polarized pulses were then used to erase these surface charges; the results are shown in Fig. 4(c). Finally, similar experiments were conducted in which the charges were injected using negative pulses and erased using positive pulses, as shown in Figs. 4(d)–(f). From the results shown in Fig. 4, it was determined that over-erasure always occurs if equal and oppositely polarized pulse heights are used to erase the surface charges. Based on these findings, the appropriate oppositely polarized pulse height can be chosen in order to neutralize certain surface charges. In particular, a large oppositely polarized pulse height is required to neutralize surface charges injected by a relatively high pulse. The slopes of the lines in Figs. 4(c) and (f), which show the surface potentials after charge erasure as functions of the oppositely polarized pulse height, increase with the initial surface potential, and the value of the surface potential tends to increase with increasing pulse height. This behavior implies that the effect of the initial surface potential on the charge erasure processes is lower for higher oppositely polarized pulses.

In addition, the effect of the oppositely polarized pulse width on the surface charge erasure was examined, as shown in Fig. 5. The surface potentials obtained when the same numbers of surface charges were injected into the surface using a pulse height of +12 V and a 1 s width are shown

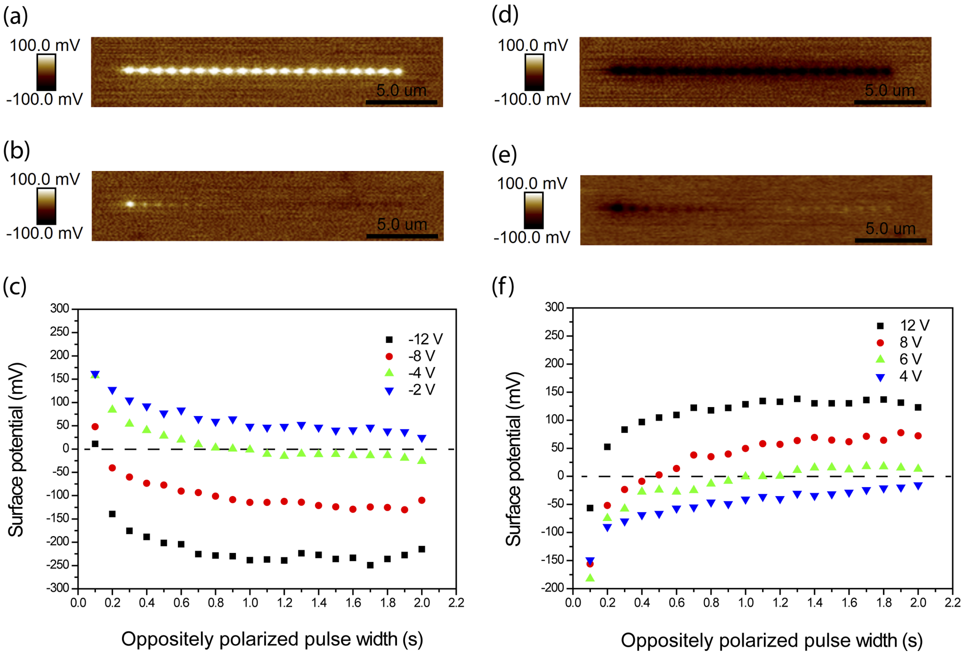

FIG. 5. Effect of oppositely polarized pulse width on surface charge erasure. (a) Surface potentials of contact points at which charges were injected using identical pulses (height: +12 V; width: 1 s). (b) Surface potentials of points following application of oppositely polarized pulse heights of −4 V for surface charge erasure; the pulse widths were varied from 0.1 to 2.1 s in 0.1-s intervals. (c) Surface potentials after charge erasure process, for oppositely polarized pulse heights of −12 (black), −8 (red), −4 V (green), and −2 V (blue). (d) Surface potentials of contact points at which charges were injected using identical pulses (height: −12 V; width: 1 s). (e) Surface potentials of points following application of oppositely polarized pulse heights of +6 V for surface charge erasure; the pulse widths were varied from 0.1 to 2.1 s in 0.1-s intervals. (f) Surface potentials after charge erasure process, for oppositely polarized pulse heights of 12 (black), 8 (red), 6 (green), and 4 V (blue).

in Fig. 5(a). An oppositely polarized pulse height of −4 V was used to erase the surface charges, where the pulse widths were varied from 0.1 to 2.1 s in 0.1-s intervals, as shown in Fig. 5(b). In addition, different oppositely polarized pulse heights with various pulse widths were used to erase

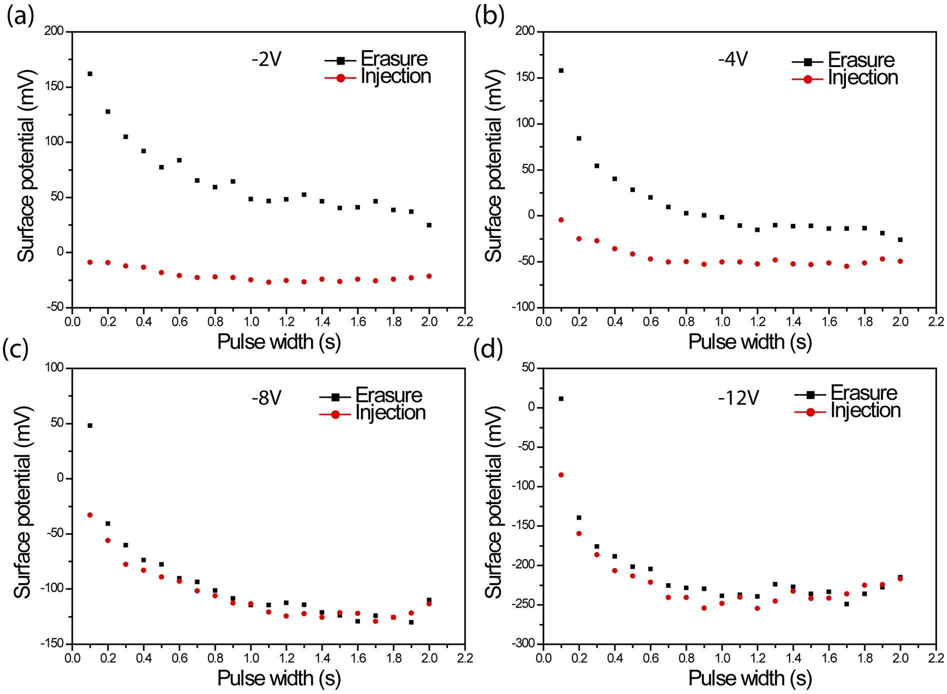

FIG. 6. Comparison of charge injection and erasure behavior for negative pulses. Pulses of (a) −2, (b) −4, (c) −8, and (d) −12 V were used to erase the initial charges, which were injected by +12-V pulses.

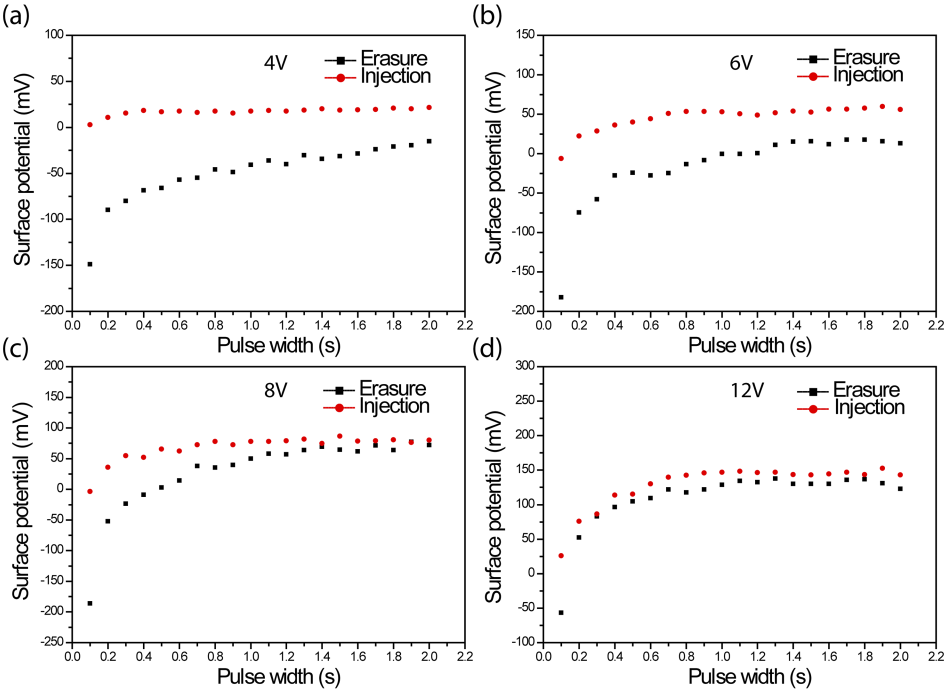

FIG. 7. Comparison of charge injection and erasure behavior for positive pulses. Pulses of (a) 4, (b) 6, (c) 8, and (d) 12 V were used to erase the initial charges, which were injected by −12-V pulses.

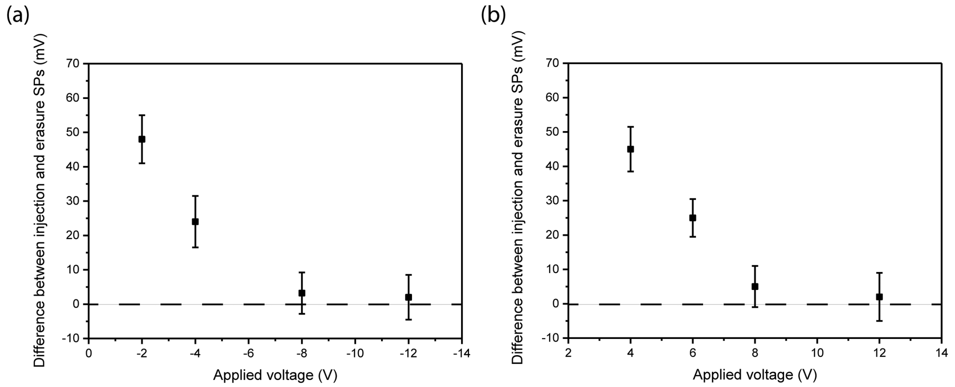

FIG. 8. Differences between surface potentials (SP) of injection and erasure processes under different applied voltages (pulse width = 2 s). For the erasure processes, the initial charges on the surface were injected by (a) +12-V and (b) −12-V pulses.

surface charges injected by pulses with +12-V height and 1-s width, and the results are shown in Fig. 5(c). Finally, Figs. 5(d)–(f) show the results of similar experiments in which the initial surface charges were induced using −12 V pulse heights, and different positively polarized pulses with various pulse widths were used to erase the surface charges. From Fig. 5, an exponential relationship between the surface potential and the pulse width of the oppositely polarized pulse was found for the charge erasure process. Hence, it is apparent that both the pulse height and pulse width can affect the charge erasure result. The oppositely polarized pulse width appropriate for neutralization of the surface charge is dependent on the oppositely polarized pulse height, where a lower oppositely polarized pulse height requires a larger pulse width to neutralize the surface charge. However, if the oppositely polarized pulse height is too low, it will be difficult to neutralize the initial potential, even in the case of a pulse width larger than 2 s.

C. Charge injection vs. charge erasure

Comparisons of the effects of the pulse width on the charge erasure and charge injection behaviors are shown in Figs. 6 and 7, for negative and positive pulses, respectively. Fig. 8 shows the differences between the surface potentials of the injection and erasure processes under various applied voltages, for a pulse width of 2 s. Hence, it is apparent that the difference between the injection and erasure processes is more significant for a lower pulse height.

IV. DISCUSSION

From the results presented in the previous section, it is apparent that charges on a dielectric surface can be neutralized using oppositely polarized pulses, the heights and widths of which are appropriately tuned. Further, if the height of the oppositely polarized pulse is sufficiently large, the difference between the charge injection and erasure processes can be eliminated. This means that the number of surface charges and their polarity are totally dependent on the oppositely polarized pulse in this scenario, and that the number of initial charges on the surface has no impact. However, if the oppositely polarized pulse height is not sufficiently large, the initial charge can affect the surface potential in the charge erasure process.

Based on these observations, we propose that an oppositely polarized charge is injected into the surface and an initial charge is removed simultaneously, when the oppositely polarized pulse is applied to the surface. It has been reported that the potential barrier formed by surface atoms can resist charge penetration into the surface.[19] However, charges under the influence of an electric field (as in the charge injection process) may obtain sufficient energy to cross this potential barrier, where they are then trapped by potential wells. Then, when an oppositely polarized electric field is applied to the interface (as in the charge erasure process), the trapped charges might be extracted from the potential wells, which causes them to leave the surface. Schematics of these charge injection and erasure processes are shown in Fig. 9. The charges are injected into the surface under the influence

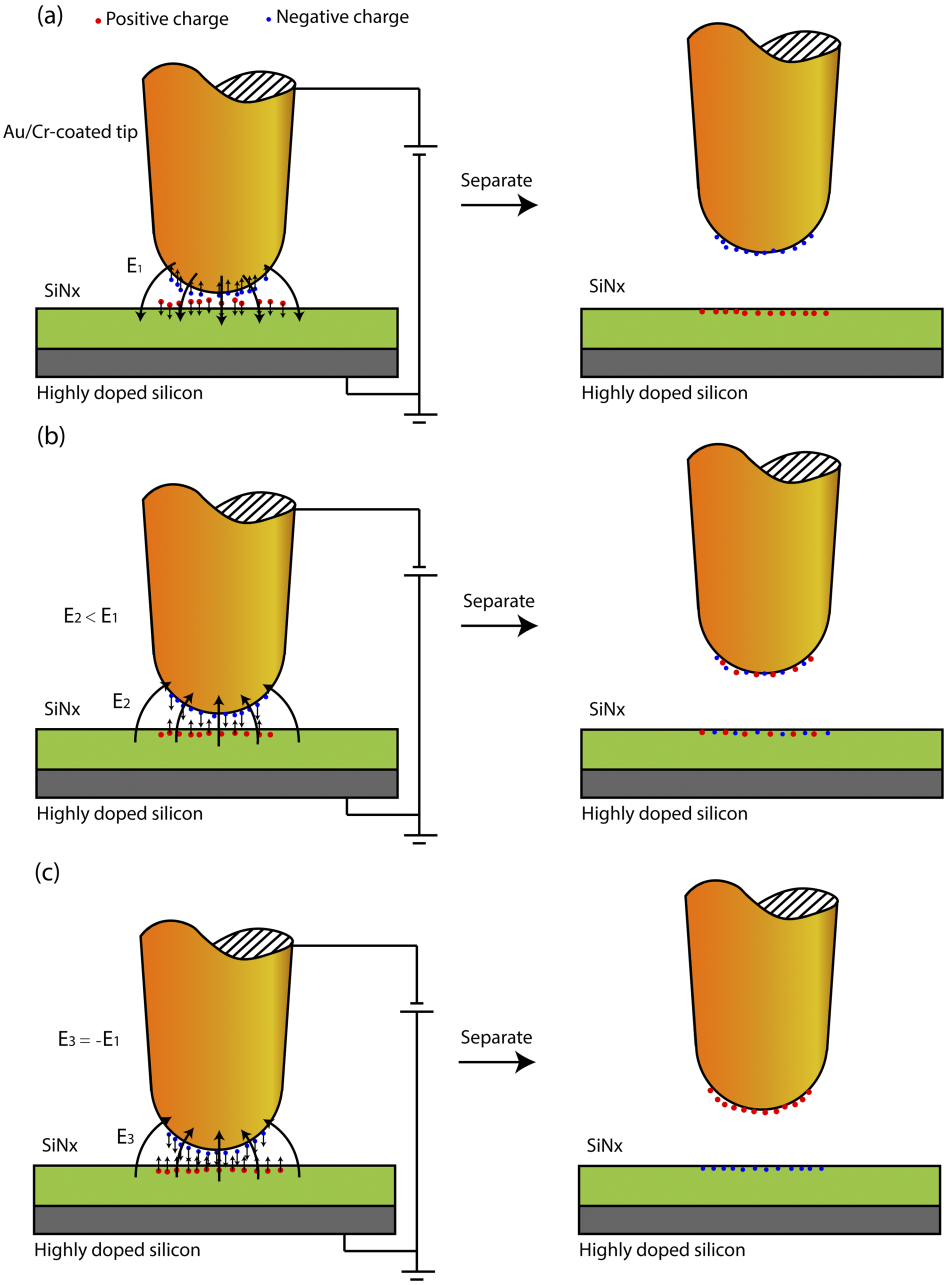

FIG. 9. Schematics of ion injection processes. (a) Surface charge injection. Processes when oppositely polarized pulse is (b) smaller than and (c) equal to initial charge. (E_1–E_3: Electric field strengths.)

of an electric field, where the number of trapped charges is affected by the electric field strength E_1, as shown in Fig. 9(a). The charges can obtain more energy under a stronger electric field, allowing them to cross a higher potential barrier; thus, more charges can be injected into the surface for greater E_1. When an oppositely polarized electric field is applied to the interface, the charges can be extracted from the surface, which allows opposite charges to be injected into the surface. As shown in Fig. 9(b), if the strength of the oppositely polarized field E_2 is smaller than E_1, some of the charges cannot obtain sufficient energy to escape the potential well. Then, the net charge remaining on the SiN_x surface should be the summation of the initial and opposite charges. When the number of initial charges left on the surface is equivalent to the number of opposite charges, the surface potential is neutralized. This is the reason why a smaller, oppositely polarized pulse can neutralize a surface charge injected by a higher pulse. Finally, as shown in Fig. 9(c), if the strength of the oppositely polarized field E_3 is equal to E_1, all the initial charges can be extracted from the potential wells, and opposite charges can be injected into surface at the same time. Hence, the number of surface charges and their polarity are dependent on the last pulse.

V. CONCLUSION

The mechanisms of charge injection and erasure on an insulating surface were examined in this study. It was demonstrated that a charge pattern on an insulating surface can be neutralized by adjusting both the height and width of an oppositely polarized pulse applied after the pattern formation. In addition, mechanisms of charge injection and erasure were proposed. It is suggested that the potential barrier formed by the surface atoms plays an important role in the charge injection and erasure processes. The net charge remaining on the surface should be the summation of the initial charges, which cannot be extracted from the potential barrier, and the opposite charges, which are injected into the potential barrier by the oppositely polarized pulses. The findings of this work provide a means of achieving data modification and preventing disruptive discharge, etc. We suggest that data modification can be achieved through direct application of a pulse with sufficient height, because the surface charge at any given time is totally dependent on the most recent pulse in this scenario. A limitation of this work is that the appropriate height and width of the oppositely polarized pulse cannot be calculated accurately for a given surface charge. In addition, the asymmetry of the charge erasure between positive and negative pulses has not yet been explained. We will focus on both of these topics in our future research.

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