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Effect of substrate on the step coverage of plasma-enhanced chemical-vapor deposited tetraethylorthosilicate films

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Plasma-enhanced chemical-vapor deposition tetraethylorthosilicate (TEOS) films are extensively used as the interlayer dielectric films in multilevel interconnection processes. When TEOS oxide films were deposited on metal patterns three different substrates, titanium nitride (TiN), aluminum (Al), and oxide (SiO_2), were used. This study examines the dependence of these substrates on TEOS step coverage. The deposition rates of TEOS oxide revealed that the SiO_2 substrate lead to highest TEOS deposition rate during the initial deposition period of 5 s. Then, the TEOS deposition rate of the substrates was nearly the same. The TiN substrate exhibited the highest sidewall step coverage but the sidewall step coverage of the Al substrate deteriorated due to its granular surface. Additionally, different substrates exhibited different coverage of the bottom step. Moreover, the bottom step coverage exceeded the sidewall coverage for all substrates. © *2003 American Vacuum Society.* [DOI: 10.1116/1.1574046]

I. INTRODUCTION

The step coverage obtained of undoped silicon dioxide glass (USG) film is very important to the microelectronic industry. Poor step coverage of deposited glass may cause a void inside a glass film. When the glass is etched back or polished during planarization, this void may be opened, and a large sharp-angled step appears. Thus poor step coverage affects yield and reliability because the metal deposited over the glass also suffers from poor step coverage, exhibiting discontinuities or thinning at the steps.[1] The step coverage has been previously reported to depend on deposition parameters, including deposition temperature, total gas flow, and substrate material.[1–3]

Chemically vapor-deposited (CVD) tetraethylorthosilicate (TEOS) oxides have demonstrated good step coverage, gap filling, planarizing capability, and electrical properties.[4,5] The application of plasma deposition in the microelectronics industry began in 1963.[4] Silicon insulator dielectrics produced by plasma-enhanced chemical vapor deposition (PECVD), such as SiO_2, represent the most important commercial microelectronic applications of PECVD. Low temperature PECVD films are found to be suitable for use as the final passivation layer in integrated circuits, and as interlevel dielectrics in multilevel metallic structures.[6,7]

The dependence of process parameters on the step coverage of silicon dioxide has been thoroughly investigated.[1–7] Low pressure CVD (LPCVD) yields better step coverage than PECVD and PECVD provides better step coverage than atmospheric pressure CVD (APCVD).[2] In LPCVD, temperature, pressure, pumping speed, TEOS flow, and the addition of gaseous additives such as N_2, Ar, O_2, and PH_3 are important factors that determine step coverage.[2] The effects of temperature and TEOS flow on step coverage in a radio frequency (rf) downstream reactor have been studied.[8] The metal profiles also influence the step coverage.[9] Plasma sources play a significant role in determining step coverage. Comparing the step coverages for different plasma sources, including microwave downstream plasma (MW), high frequency radio frequency (HF/rf) plasma, and low frequency radio frequency plasma (LF/rf), reveals that the MW system yields the best step coverage. Additionally, the LF/rf plasma system yields the poorest coverage.[10] The bottom step coverage (BSC) performs better than the sidewall step coverage (SSC) in MW downstream. However, BSC performs better than SSC in the HF/rf system.[10] The metal spacing also importantly affects step coverage.[10] The effects of precursors and substrate materials on the step coverage in metalorganic CVD (MOCVD) have been presented.[11] Adding bias or em-

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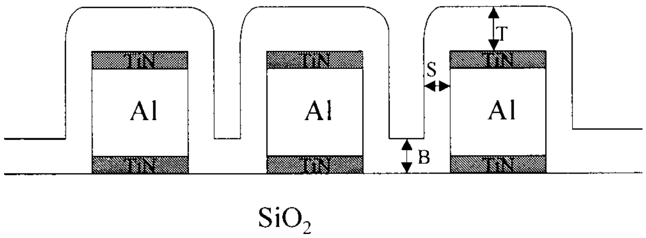

FIG. 1. Sidewall step coverage is S/T and the bottom step coverage is B/T. T, S, and B are the PE-TEOS thickness on the top, sidewall, and bottom of the trench.

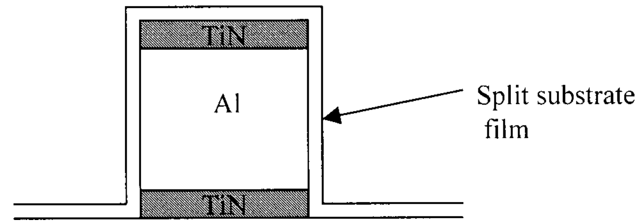

FIG. 2. Four kinds of split substrate films: (1) none, (2) SiO_2, (3) Al, and (4) TiN. These split substrate films can be regarded as the liners for PE-TEOS.

ploying ion beam resputtering improves the step coverage.[12,13] The ratio of gaseous reactants in the PECVD of silicon nitride films impacts step coverage.[14] Various models of the deposition process have been presented.[15–22]

However, the effect of substrate on TEOS silicon dioxide deposition has seldom been addressed. This investigation considers how the substrate affects the TEOS oxide in a HF/rf PECVD system. The deposition rate and step coverage of the TEOS oxide films are studied. The charge on the surface of the substrate influences the deposition rate. The characteristic granular surface of aluminum presents affects on step coverage.

II. EXPERIMENT

The commercially available Applied Material Centura DXZ chamber was used for the PECVD of TEOS silicon dioxide (PE-TEOS) film. The system was a parallel plate radio frequency (rf) plasma system. The spacing between the two electrodes was 280 mil during deposition. The rf frequency was 13.56 MHz, a fix rf matching box was used and the deposition power was 1100 W. The reactive species involved in PE-TEOS deposition were TEOS and O_2 and He was the carrier. The flow rates were the standard 900 cm^3/min (sccm) TEOS, 2700 sccm O_2, and 1000 sccm He. The deposition temperature was 400 °C. The deposition pressure was 6.5 Torr and was controlled using a step-motored throttle valve.

Two 8 in. wafers were used. One was the bare silicon wafer used to measured the PE-TEOS deposition rate. The other was the patterned wafer used to compare step coverage. The pattern was as follows. The height of the metal, including the top and bottom titanium nitride (TiN), was 600 nm. The width and spacing between the metal lines were 300 nm. The aspect ratio of the pattern was two. Figure 1 defines the sidewall and bottom step coverage. Sidewall step coverage equals S/T and bottom step coverage equals B/T.

PE-TEOS was deposited on the metal patterns using three different substrates, as shown in Fig. 1. Extra liners were added to confirm the effect of the substrate on PE-TEOS deposition. Figure 2 shows the conditions of splitting liners. Four liners were considered: none, Al, TiN, and SiO_2. The thickness of the deposited liner was about 10 nm.

Al and TiN liners were deposited using common commercial physical vapor deposition (PVD) Applied Material Endura cluster tools. The target used for the Al liner was Honeywell 99% Al+0.5% Cu. The Al liner deposition power was 2500 W and the temperature was 300 °C. The argon (Ar) gas flow rate was 33 sccm. The target used for TiN liner deposition was Honeywell 99.999% Ti. The TiN liner process power was 6500 W and deposition was performed at room temperature. The TiN deposition gas flow rate was 50 sccm Ar and 100 sccm N_2. The SiO_2 liner was deposited using a commercial Applied Material Centura DXZ chamber with postdeposition plasma treatment. The reactive species in the SiO_2 liner deposition were TEOS and O_3 and He was the carrier. The flow rates of the reactants were 280 sccm TEOS, 5000 sccm O_3, and 4000 sccm He. The O_3 concentration was 13%. The deposition temperature was 400 °C. The deposition pressure was 450 Torr. The rf frequency for postdeposition plasma treatment was 450 KHz, a fix rf matching box was used, and the treatment power was 700 W. Silicon nitride (NIT) was deposited as a capping layer for metal patterns. NIT was deposited using a commercial Applied Material Centura DXZ chamber. The reactive species in NIT deposition were 315 sccm SiH_4, 120 sccm NH_3, and 4000 sccm N_2O. The deposition temperature was 400 °C and the pressure was 4.8 Torr.

The deposition thickness and the step coverage of the PE-TEOS films were measured using scanning electron microscopy (SEM). The SEM system was a Hitachi 4500. The surface charges on the different substrates were measured using a KLA&Tencor Quantox Keithley instrument.

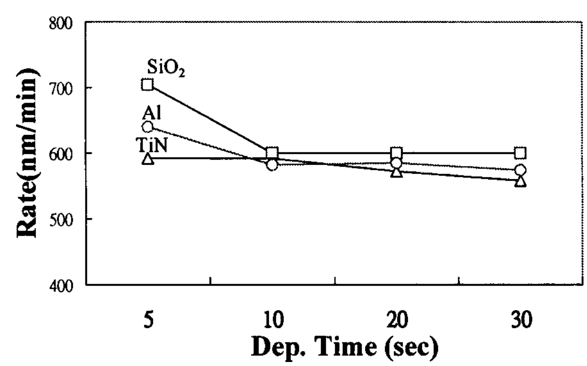

FIG. 3. Dependence of the deposition rate of PE-TEOS films on different substrates.

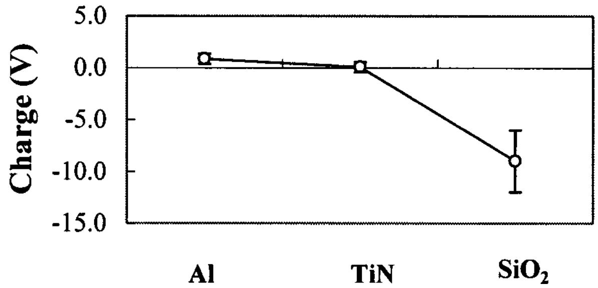

FIG. 4. Dependence of surface charge on the substrates. The thicknesses of Al, TiN, and SiO_2 are 400, 140, and 400 nm, respectively.

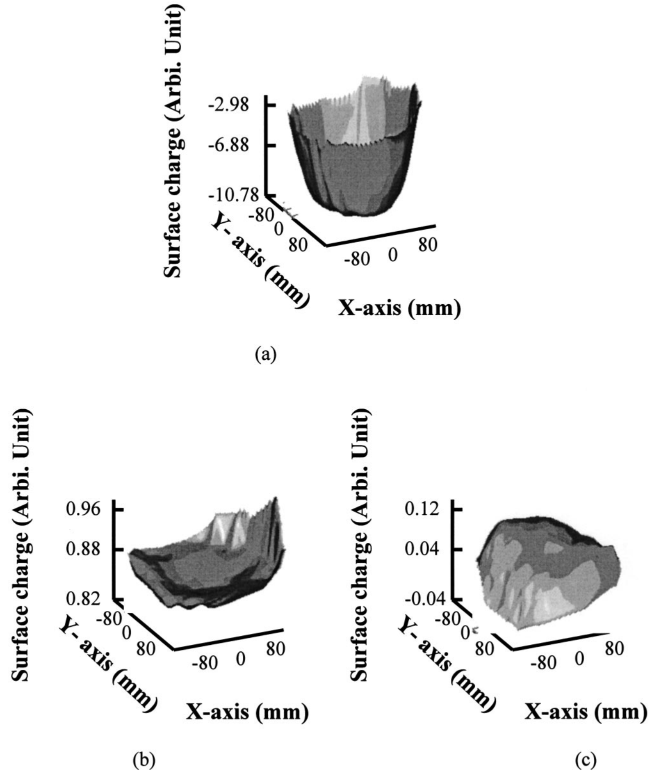

FIG. 5. Surface charge distribution for different substrates. (a) SiO_2, (b) Al, and (c) TiN. The thicknesses of Al, TiN, and SiO_2 are 400, 140, and 400 nm, respectively.

III. RESULTS AND DISCUSSION

A. Blanket wafers

Figure 3 plots the dependence of the deposition rate on the type of substrate. Except deposition time (sec), the deposition parameters, including the flow rates of the reactive gases, the temperature, the pressure, and the spacing between the electrodes, were all held constant. According to our results, TEOS SiO_2 (PE-TEOS) was deposited most quickly on the SiO_2 substrate with a deposition time of 5 s. The TiN substrate yielded the slowest PE-TEOS deposition in the first 5 s. The thickness of the deposited PE-TEOS on SiO_2 was 59 nm and that on the TiN substrate was 49 nm in the initial 5 s of deposition. The difference between the initial PE-TEOS deposition rate on SiO_2 and that on TiN was approximately 20%. Increasing the deposition time hardly changed the deposition rates of PE-TEOS on the various substrates.

PECVD generally involves the radical and ionic mechanism,[6,7] which can be enhanced by adjusting the deposition parameters.[6,7,9] The ionic mechanism of PECVD with the high frequency rf configuration is more significant than that of the microwave downstream system.[10] Generally, PECVD deposition can be divided into four major steps:[6] (1) Electrons react with reactants to form a mixture of radicals and ions. (2) Reactive species move to the substrate's surface. (3) Reactive species react with or are adsorbed by the substrate surface. (4) The film growths or reactive species are

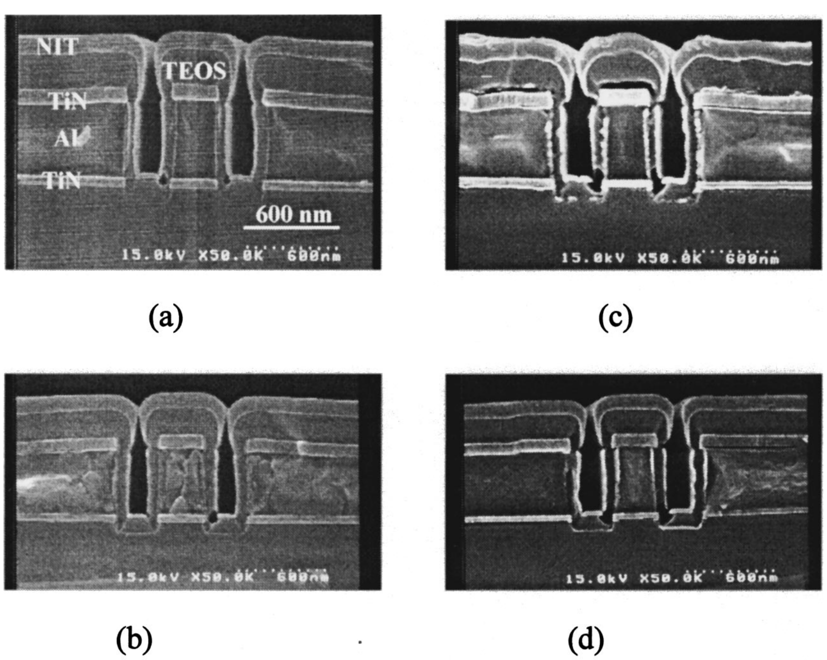

FIG. 6. SEM photographs of PE-TEOS deposited on different liners. (a) No liner, (b) SiO_2, (c) Al, and (d) TiN. Silicon nitride (NIT) is 100 nm and PE-TEOS 200 nm.

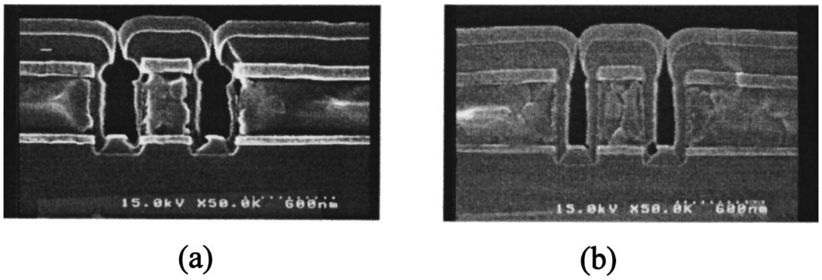

FIG. 7. SEM photographs of PE-TEOS deposited on SiO_2 liners with different etching time using 100:1 ($HF:H_2O$) solution. (a) 8 s and (b) 3 s.

reemitted into the gas phase. Step (3) is the rate-limiting step.

Figure 4 presents the dependence of the surface charge on the type of substrate. Figure 5 shows surface charge distribution within the 8 in. blanket wafer for different substrates. The SiO_2 substrate is associated with the greatest surface charge, which was negative. The Al surface had a moderate positive charge. The TiN surface was almost uncharged. The differences among the surface charges were associated with the different deposition processes used. SiO_2 was deposited by PECVD with postnitrogen plasma treatment. Al was prepared by traditional PVD. TiN was formed by reactive PVD. The order of the surface charges corresponded to the PE-TEOS deposition rate during the initial deposition period. The PE-TEOS deposition rate did not differ with deposition time because the surface effect was eliminated after the surfaces were covered with PE-TEOS.

In the O_2/He plasma, the well-known Penning effect[6] generates oxygen radicals or ions, according to Eq. (1):

$$\mathrm{He}^* + \mathrm{O}_2 \rightarrow \mathrm{He} + 2\mathrm{O} \quad \text{or} \quad \mathrm{He} + \mathrm{O}_2^+ + e. \tag{1}$$

TEOS decomposes due to the impact of electrons or a chemical reaction with gas phase radicals:

$$\mathrm{TEOS} + (e, \mathrm{O}, \text{ or } \mathrm{O}_2^+) \rightarrow I, \tag{2}$$

where I represents the decomposition intermediate of TEOS. Intermediate I diffuses to the substrate's surface and is adsorbed onto it; it then reacts with another I and so on to generate the SiO_2 network:

$$I + I \xrightarrow{\text{surface}} \mathrm{SiO}_2. \tag{3}$$

Notably, Eq. (3) is bimolecular; therefore the deposition rate depends only on the concentration of I. Figure 3 reveals that the PE-TEOS deposition rate was higher on the SiO_2 and Al surfaces than on the TiN substrate because the surface charge promotes the adsorption or reaction of the intermediates on the substrate. Consequently, the surface charge accelerates the reaction described by Eq. (3). A higher surface charge corresponds to a higher rate of deposition of PE-TEOS.

B. Patterned wafers

Figure 6 displays scanning electron microscopy (SEM) photographs of PE-TEOS deposited on different substrates (liners). Silicon nitride (NIT) was the cap on every sample and the NIT thickness was 100 nm. Except for the sample of the SiO_2 liner, the SEM samples were all softly etched using 100:1 ($HF:H_2O$) solution for 8 s to enhance the different layers. The sample of the SiO_2 liner was etched for 3 s. Figure 7 presents SEM photographs of the SiO_2 liner with different soft etching time. These photographs show that the PE-TEOS film on the trench sidewall was easily etched away. Implying that PE-TEOS deposited on the SiO_2 liner was a little more porous than that deposited on other liners. The aforementioned higher deposition rate of PE-TEOS on the SiO_2 liner could explain this finding. The thickness of the deposited PE-TEOS was about 200 nm. The width and height of the metal patterns were 300 and 600 nm, respectively. The metal spacing was 300 nm. Table I summarizes the step coverage of different liners. The bottom step coverage hardly differed among the various liners. The bottom step coverage exceeded the sidewall step coverage under all experimental conditions. These results were consistent with those of Mort and Jansen,[7] Selamoglu *et al.*,[8] and Raupp and Cale.[23]

The TiN liner yielded the best SSC. The SiO_2 liner yielded similar SSC data to those for PE-TEOS. However, the Al liner exhibited poor PE-TEOS SSC. The data concerning deposition rate using the blanket wafer, SiO_2 surface yielded the highest PE-TEOS deposition rate. A deposition rate on the top of the metal pattern that is too high causes an overhang to form. The overhang hinders the reactive species from being deposited on the sidewall. Yi *et al.*[4] and Gao and He[11] previously reported this shadowing effect. Figure 6 indicates that the SiO_2 liner suffered a slightly worse overhang than Al and TiN as evidenced by the least distance between the NIT films at the top corners of the trench. Accordingly, the SiO_2 liner improved the deposition rate of PE-TEOS but did not give the best SSC results.

Table I shows that the TiN liner yielded the best SSC for PE-TEOS. The TiN liner formed the three originally different surfaces of the deposited trench into just a single type; that is, it made the top, sidewall, and bottom surfaces of the trench equivalent material. Figure 4 indicates that the TiN

TABLE I. PE-TEOS step coverage for different liners.

Liner	None	TiN	Al	SiO_2
S/T[a]	41%	47%	35%	44%
B/T[b]	63%	63%	65%	63%

[a]S/T: sidewall step coverage.
[b]B/T: bottom step coverage.

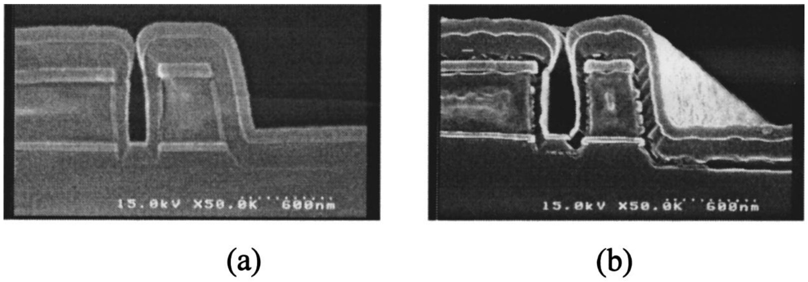

FIG. 8. Granular surface effect on PE-TEOS deposition. (a) SiO_2 liner and (b) Al liner. Sample (a) is etched using 100:1 ($HF:H_2O$) solution for 3 s and (b) 8 s.

surface was uncharged. Thus the SSC data obtained for the TiN liner performed optimally with respect to excluding the substrate effect in PE-TEOS deposition.

The poorest SSC results were obtained for Al liners because of their granular surface. Figure 8 clarifies the effect of the granular surface. The PE-TEOS on the sidewall exhibited a wrinkled morphology when Al liners were used. The wrinkled morphology of PE-TEOS was clearly related to the granular surface of the Al liner. The step coverage data in Table I show that the granularity of the Al surface decreased the rate of deposition of PE-TEOS. The mechanism of the effect of the granular surface on the PE-TEOS deposition requires further study. However, the dependence of sticking coefficient (S_C) of the reactive species on the step coverage has been extensively investigated.[15,23,24] As S_C for reactive species increases, the reactive species undergo fewer collisions with the surfaces of the enclosure before reacting. The S_C values reduce conformal deposition.[15,23,24] Thus the low sidewall step coverage of the Al liner is related to a high S_C value because of the granular surface. Figure 9 shows the dependence of the granular liner on the transport mechanism of the reactive intermediates. The granularity of the surface reduces the probability of reemission and surface diffusion of the reactive intermediates. Therefore the PE-TEOS SCC performance was poor when it was deposited on the granular Al surface.

IV. CONCLUSIONS

This study has examined the dependence of the step coverage of PECVD TEOS oxide film (PE-TEOS) on the type of substrate. Aluminum (Al), titanium nitride (TiN), and silicon dioxide (SiO_2) were used as the liners deposited before PE-TEOS deposition. During the initial deposition period (5 s), the SiO_2 substrate exhibited the highest PE-TEOS deposition rate. The deposition rate on the SiO_2 substrate was 19% higher than that on TiN and 10% higher than that on Al. Increasing the deposition time did not clearly change the effect of the substrate on the PE-TEOS deposition rate. The surface charge on different substrates was measured and the results showed that the SiO_2 substrate had a negative charge, the Al substrate was positively charged, and the TiN surface was almost uncharged. The charge on the SiO_2 surface was four times that on the Al surface, increasing the initial deposition rate of PE-TEOS.

The experimental liners included Al, TiN, and SiO_2. The TiN liner yielded the best sidewall step coverage in PE-TEOS deposition. The TiN liner showed 6% improvement in the sidewall step coverage compared to the no-liner condition. The SiO_2 liner showed similar step coverage to the no-liner case. The Al liner had a PE-TEOS sidewall step coverage of around 6% less than the no liner because of the granularity of its surface. The sticking coefficient S_C of the granular surface of the Al liner was higher than that of the other surface for reactive species. As the reactive sticking coefficient S_C increased, the reactive species underwent fewer collisions with the surfaces of the enclosure before reacting. Thus a high sticking coefficient S_C reduces conformal deposition.

The actual PECVD process is undoubtedly complicated. This research presented that the characteristics of the substrate greatly affected the deposition process. These results gave us more knowledge about the PECVD mechanism.

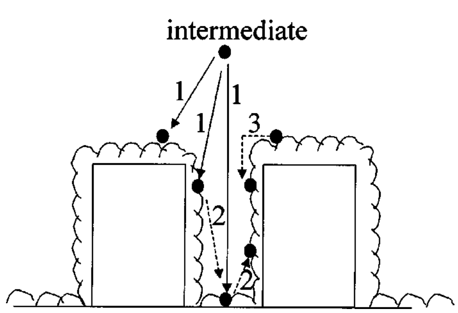

FIG. 9. Dependence of the granular liner on the move of the intermediates. 1: direct adsorption, 2: reemission, and 3: surface diffusion.

ACKNOWLEDGMENT

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