SURFACE MODIFICATION OF MIXED SELF-ASSEMBLED MONOLAYER BY CU(I)-CATALYZED CYCLOADDITION AND ESTER HYDROLYSIS

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ABSTRACT : Organic reactions in small dimension of space in mixed self-assembled monolayer have been performed and characterized by contact angle measurement and XPS. Mixed self-assembled monolayers, containing both azido and acetylene terminal groups homogeneously distributed across the surface, were prepared by dipping Au substrates into mixed solutions of azido disulfide and acetylene disulfide at equal concentrations. The mean value of water contact angle measurement on the surface compared to mono-functional azido and acetylene monolayers suggesting the gold substrate was homogenously covered by mixture of azido and acetylene terminal groups at the desired ratio. The surface was further treated with Cu(I) catalyst solution followed by alkaline solution. Water contact angle measurement of mixed monolayer dropped significantly after the treatments shows the surface has been modified from hydrophobic into hydrophilic surface character. The result is consistent with XPS analysis at narrow scan of C and N elements i.e. the presence of a signal at 289 eV for carbonyl group and disappearance of azido signal at about 400 eV. This experiment was reflecting sequential intramolecular organic reactions of cycloaddition and hydrolysis of ester in mild condition on single layer of activated functional groups of organized ultra thin film.

KEYWORDS : Self-assembled monolayer, cycloaddition, hydrolysis, intramonolayer

INTRODUCTION

Organic reaction on a surface is as crucial as physical and interfacial interactions. Active functional groups on a surface may react in the presence of certain reagents and appropriate conditions. With recent advanced study on self-organized structures, the prospect of organic reactions system have encouraged people for further investigating the mechanism of reactions, factors that influence the reactions on the surface and how it can be useful for certain potential applications.

There are some examples of self-organized structures that have been used for investigating organic reactions. Vesicular structure, for example, has been used to provide binding site and as a catalyst for deprotonation of 6-nitrobenzisoxazole (Pérez-Juste et al., 2000). 1,3-dipolar cycloaddition reactions have been observed and effectively accelerated in the presence of micelles (Rispen & Engberts, 2003) and microemulsions (Engberts et al., 2006). There are also less dynamic self-assembled structures used for similar purposes such as polymeric solid-support for 1,3-dipolar cycloaddition reactions (Rück-Braun, Freysoldt & Wierschem, 2005). Cycloaddition reaction also has been performed on self-assembled monolayer and well analyzed by electrochemical measurement (Collman et al., 2006; Collman et al., 2004). It has been learned that most of the studies involving organic reactions on monolayers very often representing intermolecular reactions, particularly cycloaddition as our main subject on chemical reactions.

In this report, we will discuss on the intramonolayer reaction of 1,3-dipolar cycloaddition between terminal groups of azido and acetylene on mixed monolayer system. The mixed monolayer of azido and acetylene was treated with Cu(I) catalyst followed by hydrolysis of ester to observe any surface modification. Water contact angle measurement dropped significantly after the reactions. This shows that the azido and acetylene terminal groups have reacted but hydrolysis of ester leaves the surface mostly with hydroxyl and carboxylic acid terminal groups. The wetting of surface phenomena corresponds with XPS at narrow scan of N where doublet signal of azido has disappeared after the reactions. The reactions were also performed in reversed order as a background study which showed no further reactivity on the surface after removing the azido moiety from the monolayer.

MATERIALS AND METHODS

Disulfide compounds 1 and 2 (Figure 1) for the formation of self-assembled monolayers were prepared and purified before being applied to the gold substrate. These compounds were analyzed by Nuclear Magnetic Resonance (NMR), Fourier Transform InfraRed (FTIR) and Mass Spectrometer (MS) to confirm the structures. In this part, we also discuss on the cleaning process of glass slides and preparing gold coating on the glass slides.

The preparation of mono-functional and also mixed SAMs (self assembled monolayers) is shown in Figure 1.
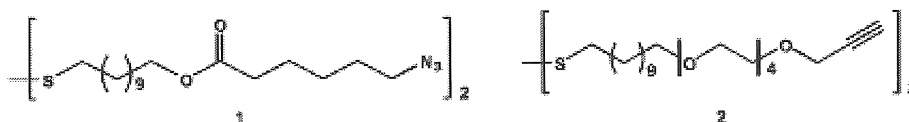

Figure 1. Molecule structures of disulfides compounds 1 and 2 that were used for the formation of self-assembled monolayers on gold substrate

Materials

6-Azidohexanoic acid:

Azido compound was prepared by displacement of 6-bromohexanoic acid with azide sodium salt in DMSO in equal moles. The crude was further purified from column chromatography to produce 86 % of fine yield in a liquid form. R_f = 0.67 (1:1 ethyl acetate:hexane, $KMnO_4$). ^1H NMR (250 MHz, $CDCl_3$): δ 3.27 (t, J = 6.7 Hz, $-CH_2N_3$, 2H), 2.37 (t, J = 7.5 Hz, $-CH_2$ COOH, 2H), 1.72-1.35 (m, $-CH_2-$, 10H). FT-IR: 3101, 2943, 2868, 2098, 1709 cm^{-1}. EIMS: *m/z* 158 [M+H], 175 [M + NH_4^+]; high resolution MS calculated for $C_6H_{10}N_3O_2$ is 156.0073, found 156.0773.

Di-[11-(6-azidohexanoate)-1-undecyl] disulfide (1):

The disulfide 1 was prepared by esterification of di-11-hydroxyl-1-undecyl disulfide and 6-azidohexanoic acid (Tajuddin, 2007). The di-11-hydroxyl-1-undecyl disulfide was prepared and purified using the method as reported by Wrighton *et al.*, (1995). We were able to produce 23 % of fine yield in a liquid form. R_f = 0.85 (1:3 ethyl acetate:hexane). ^1H NMR (250 MHz, $CDCl_3$): δ 3.99 (t, J = 6.7 Hz, $-CH_2OCO-$, 4H), 3.21 (t, J = 6.9 Hz, $-CH_2N_3$, 4H), 2.61 (t, J = 7.3 Hz, 4H, $-CH_2S-$), 2.25 (t, J = 7.5 Hz, $-CH_2COO-$, 4H), 1.65-1.21 (m, $-CH_2-$, 48H). FT-IR: 2920 (s), 2850 (s), 2096 (s), 1727 (s), 1237 (b) cm^{-1}. ESMS: *m/z* 684 [M - H], 686 [M + H], high resolution MS calculated for $C_{34}H_{64}N_6O_4NaS_2$ is 707.4328, found 707.4326.

Di-[propargyl-11-tetraethylene ether undecyl] disulfide (2):

Compound 2 was prepared from a few steps of reactions according to the preparation by Choi *et al.*, (2004). The final step of reaction involving substitution reaction between di-[11-tetraethylene ether undecyl] disulfide and propargyl bromide in the presence of sodium hydride. The crude was purified from column chromatography to give 44 % of fine yield in

yellowish liquid form. R_f = 0.5 (2:1 ethyl acetate:hexane). ¹H NMR (250 MHz, CDCl₃): 4.14 (d, J = 2.5 Hz, CHC**CH₂**-, 4H), 3.64-3.55 (m, -O**CH₂CH₂**O-, 28H), 3.53-3.50 (m, CHCCH₂O**CH₂**-, 4H), 3.38 (t, J = 6.9 Hz, -OCH₂CH₂OC**H₂**-, 4H), 2.61 (t, J = 7.3 Hz, -**CH₂**S-, 4H), 2.36 (t, J = 2.5, **CH**CCH₂-, 2H), 1.63-1.20 (m, -**CH₂**-, 36H); FT-IR: 3250 (b), 2926 (s), 2855 (s), 1463 (s), 1106 (s) cm⁻¹; ESMS: *m/z* 836 [M+H]⁺, high resolution MS calculated for C₄₄H₈₂O₁₀NaS₂ is 857.5247, found 857.5228.

Glass slide cleaning:

Clean glass slides must be used in this process. Glass slides were cleaned with piranha solution that was prepared from a mixture of 3:7 v/v of hydrogen peroxide (30 %) and concentrated sulphuric acid. [Caution: Extra care has to be taken because the piranha solution produces very rigorous exothermic reaction and may explode if in contact with organic substance.] Then, the slides were washed with copious of distilled deionized water and dried in oven for overnight.

Preparation of gold substrates:

The clean glass slides were placed on a holder and appropriate amount of chromium and gold wire were placed on their heating coil or boats. The process started by evaporating chromium at around 5 nm thickness as an adhesive layer. Then, gold was evaporated to produce about 50 nm thickness of gold layer.

Preparation of solutions:

All disulfide solutions were prepared at 0.5 mM in degassed THF in 250 ml volumetric flask. The solution of Cu(I)-catalyst was produced freshly by preparing a mixture of 5 mM of CuSO₄ and 25 mM sodium ascorbate in 4:1 ethanol:water solvents system. For base-catalysed hydrolysis, an alkaline solution was used by preparing 0.5 M sodium hydroxide in 4:1 methanol:water solvents system.

Preparation of SAMs:

In general, the preparation of SAMs requires a clean gold substrate to be dipped into a solution of disulfide compound. A complete coverage of disulfide compounds on gold requires at least about 5 hours dipping process. The slide was taken out from the solution and washed thoroughly with ethanol. In order to prepare difunctional SAMs (mixed SAM), similar procedure was applied but using a solution of mixed disulfide compounds in equal volume of each solution **1** and solution **2**.

Reactions on mixed SAMs:

The cycloaddition reaction and hydrolysis of ester have been utilized on both randomly mixed SAM that was prepared from 1:1 mol ratio of disulfides compounds. Firstly, the surfaces were treated in the solution of Cu(I) catalyst for 12 hours and washed thoroughly with water, followed by 5 % HCl and finally by ethanol. The surface was dried under a flow of nitrogen. The surfaces were treated with the alkaline solution for another 12 hours and washed with water and ethanol. The surfaces were dried again under a flow of nitrogen.In a control experiment, similar surfaces were treated with the reagents in reversed order, which include hydrolysis of ester followed by Cu(I)-catalysed cycloaddition reaction. All samples were analysed by water contact angle (CA) measurement and XPS.

RESULTS AND DISCUSSION

Formation of SAMs

The formation of SAMs on gold was analysed by CA measurements. The CA of SAMs from compound **1 (SAM1)** and compound **2 (SAM2)** were measured at 70.3° ± 1.0 and 55.3° ± 1.3 respectively. Both compounds gave distinctive result of CA on gold surface. It is suggested that **SAM1** is more hydrophobic than **SAM2**. The CA of **SAM2** is lower than **SAM1** because of the less ordered and hydrophilic ethylene glycol within the SAM.

SAM1 was further investigated by XPS. A doublet peak in the range between 400 and 406 eV indicates the presence of N element that is from azido group **(Figure 2)**. The elements of the functional group could be assigned as one unit of sp N at 401.5 eV and two units of sp^2 N at 405 eV.
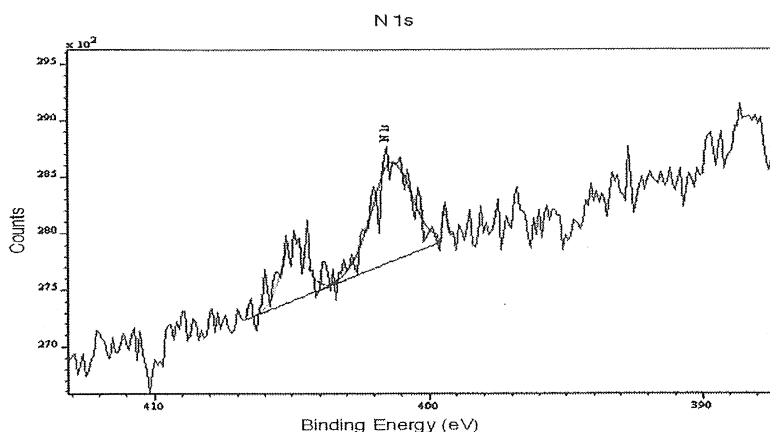

Figure 2. XPS result at narrow scan of N element shows the presence of azido moiety as a terminal group of *SAM1*

In a different experiment for the formation of **SAM2**, a gold substrate was dipped in a solution of acetylene disulfide at various times. The plot of CA increases in the beginning and reaches a plateau at around 63° after about 6 hours dipping time **(Figure 3)**. It indicates that a full coverage of **SAM2** was formed on the gold surface.
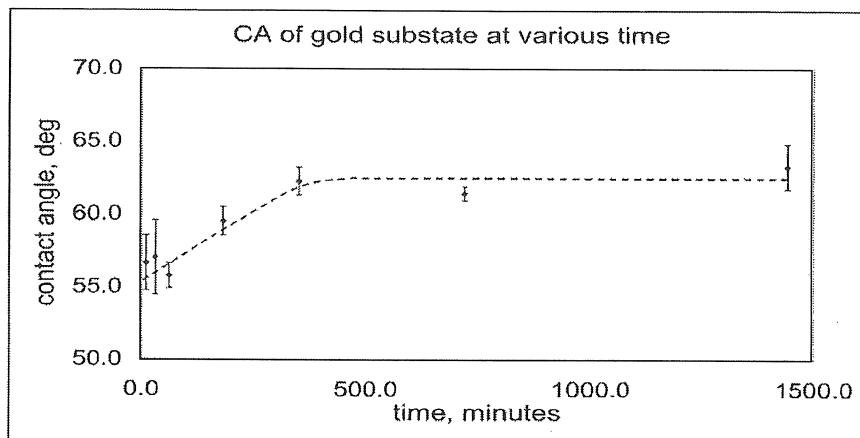

Figure 3. *The formation of acetylene terminated SAM was monitored using the water contact angle test at different period.*

When the two adsorbates were used in 1:1 mol ratio, the CA was measured at 66° ± 1.8 which is the mean value of **SAM1** and **SAM2**. It is suggested that the homogenously mixed SAM was produced from both acetylene and azido terminal groups.

The formation of mono- and di-functional SAMs was obtained through dipping of the gold substrates in the desired alkyl disulfide solutions. The coverage of monolayers on gold does not change the physical appearance but it is powerful enough to change the surface properties of gold surface. It could be an important method on how to change a flat metal substrate at nanoscale and is still useful for certain applications such as immobilization of biochemical compounds (Houseman & Mrksich, 1999; and Chapman, Ostuni, Yan & Whitesides, 2000). In our case, the presence of key element N from the azido group has been detected on the surface. It also reveals that the absorption of disulfide compounds on gold is a reliable way of anchoring other functional groups in organised structure.

Reactions on mixed SAM

The reaction of mixed SAM treated with Cu(I)-catalyst and alkaline solutions were analysed by measuring the CA as shown in **Figure 4**. The CA of mixed SAM was slightly reduced to about 62.8 ° ± 2.8 after treatment with the solution of Cu(I)-catalyst and further reduced to

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$35.2° \pm 1.8$ after treatment with the alkaline solution. The decrease of CA can be explained by intramonolayer cycloaddition between adjacent terminals of azido and acetylene and hydrolysis of ester leaving the carboxylic acid terminal on SAM.

The mixed SAM treated with reversed reactions showed that the CA was reduced only after hydrolysis but not after treated with Cu(I) catalyst. It seems that by removing azido from the surface, the cycloaddition reaction could not occur.
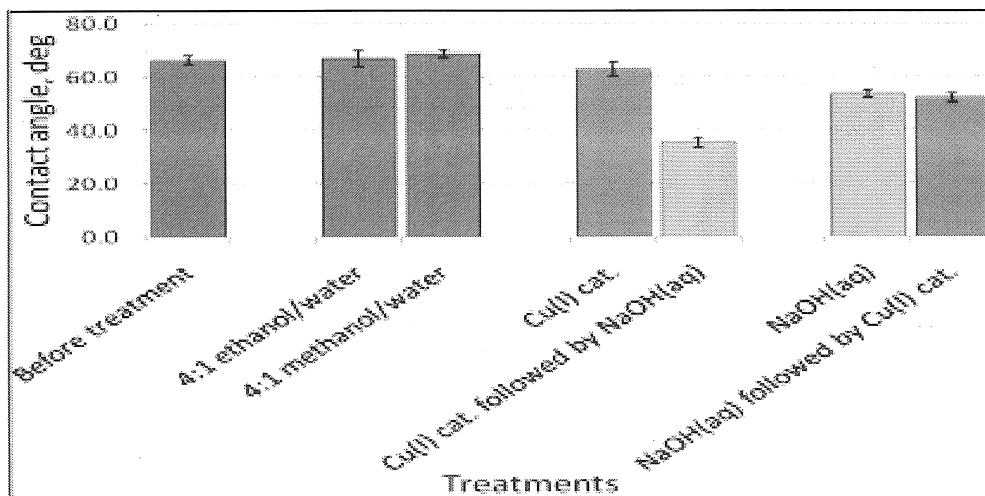

Figure 4. *The sequential reaction involving cycloaddition reaction followed by hydrolysis caused the CA on mixed SAM to decrease (C2) but by reversing the sequence causes cycloaddition reaction to stop (D2).*

The samples before and after the reactions were further analysed by XPS. In a narrow scan of N element, a weak doublet signal at 407 and 401 eV has been observed for samples before the reactions. After the reactions, the doublet signal has disappeared probably due to the formation of triazole from cycloaddition between azido and acetylene. However, there is no appearance of singlet signal as expected probably due to its weak intensity.
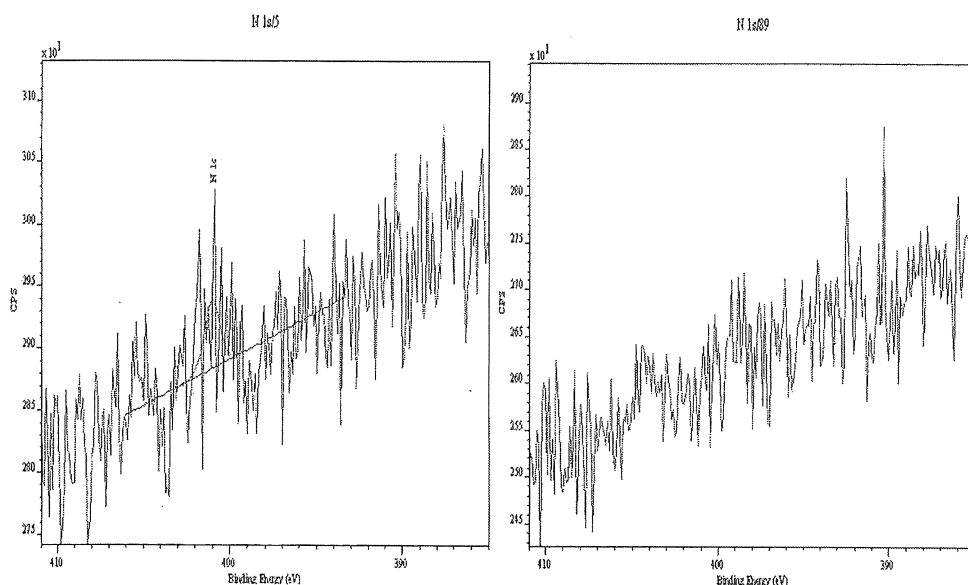
Figure 5. *A weak doublet signal (left spectrum) represents azido disappears after the mixed SAM was treated with Cu(I) catalyst and basic solution. Right spectrum is for the mixed SAM after the reactions.*

In a narrow scan of C element, both surfaces before and after the reactions have major signals at 287 eV and 285 eV which indicates the presence of C-C and C-O components with a reasonable ratio at about 2.8:1. The composition of ethylene glycol and saturated hydrocarbon on the surface confirms the formation of mixed SAM. The most important signal is at around 289 eV. The signal appeared in the spectrum after the sequential reactions but not in the spectrum after the reactions are in reversed order (**Figure 6**). These could be due to the presence of C=O in both mixed SAM and the SAM after the sequential reactions. The signal does not appeared in the SAM treated in reversed order suggesting that C=O component has been removed from the surface. Removal of azide from the surface causes the elimination of cycloaddition reaction.
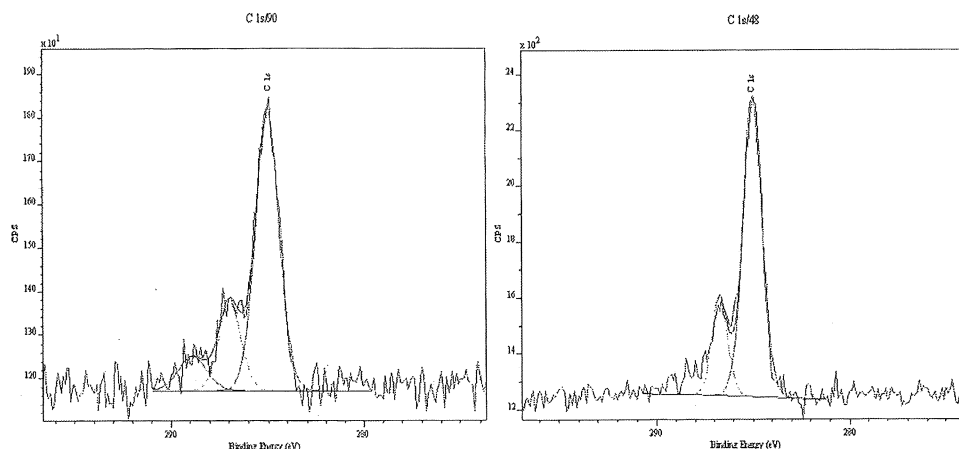
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Figure 6. *Narrow scan of C element shows the presence of key signal at around 289 eV (left spectrum) indicates the presence of C=O which does not appear in mixed SAM after the reaction in reversed order.*

Both CA and XPS data corresponds to the interaction between azido and acetylene terminal groups in the presence of Cu(I) catalyst on a mixed monolayer system that triggers or catalyze the cycloaddition reaction to produce a triazole linker amongst the monolayer (Figure 7). The change on the surface was not obvious due to similar composition of moieties on the surface before and after cycloaddition. Fortunately, the presence of ester within the mixed monolayer was ready to be hydrolyzed and leaves the surface with carboxylic acid and hydroxyl terminals. Ester group accommodates the surface modification very well as it was shown that the reactions performed in reversed order prevented the cycloaddition. The only change was on the hydrolysis of ester and cleavage of the 6-azidohexanoate from the surface to leave acetylene and hydroxyl terminal groups on the surface.
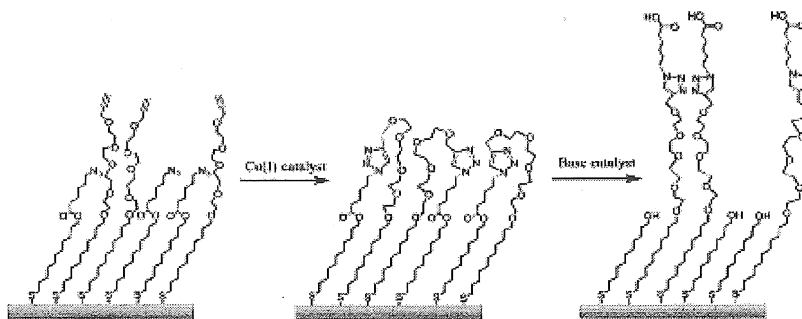

Figure 7. *Mixed SAM was initially treated by Cu(I)-catalyst allowing cycloaddition on SAM. The results of hydrolysis of ester by base catalyst was the leaving carboxylic acid on the surface.*

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CONCLUSION

Intramonolayer reaction on mixed system has been carried out by utilising Cu(I) catalysed cycloaddition reaction between azido and acetylene terminal groups. At molecular level, this produced two immobilised molecules linked to each other. Although the process is probably not easily scrutinized, the surface was obviously modified at the surface of the monolayer. The presence of the second reaction such as hydrolysis of terminal ester leaving carboxylic acid-on the surface is an evidence of the successful of intramonolayer reactions. This could be a method to control functional groups and their reactions within monolayers and perhaps a reliable way to prepare smart materials and probes at molecular scale.

ACKNOWLEDGEMENT

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