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Secondary ion mass spectrometric signal enhancement of phosphatidylcholine dioleoyl on enlarged nanoparticles surface

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ABSTRACT

A silicon wafer surface coverage of nanoparticles (NPs) can enhance the L-α-phosphatidylcholine dioleoyl (DOPC) signal intensity in time-of-flight secondary ion mass spectrometry (TOF-SIMS). A ToF-SIMS mass spectrometer was used with a pulsed primary beam of focused 30 keV Bi_3^+ ions. The signal enhancing effect has been studied for metallic (Ag, Au, Pb), semiconductor (TiO_2), dielectric (SiO_2) and hybrid (Au/TiO_2NPs, core–shell Au/SiO_2) nanoparticles. Ag NPs can attenuate secondary ions signal, whereas all other studied NPs show the signal enhancement. The emission of DOPC lipid secondary ions immobilized on core–shell Au/SiO_2NPs was enhanced up to 42 times. This technique is a simple preparatory method enabling an overall increase in molecular lipid ions.

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1. Introduction

The development of new methods for obtaining information on the organization and dynamics of assemblies is an important frontier in structural biology and mass spectrometry imaging is becoming a significant complementary technique [1,2]. Secondary ion mass spectrometry coupled with a time-of-flight mass spectrometer (ToF-SIMS) imaging technique, using a cluster ion beam as primary bombardment particles, is now an analytical tool of reference for high lateral resolution imaging ∼1 μm of biological surfaces, lateral resolution better than 100 nm is possible with specialized instruments [2]. The majority of SIMS analyses of lipid membranes has been performed using ToF-SIMS. As the large molecular fragments often have distinctive masses, labeling is, in principle, not required for component identification. Winograd and coworkers [3,4] have pioneered the ToF-SIMS analysis of domain formation in Langmuir–Blodgett lipid monolayers deposited onto self-assembled monolayers of alkane thiols on gold.

While ToF-SIMS provides a glimpse of the composition of a surface, it is still a major challenge for ToF-SIMS analysis to overcome the low secondary ion yield in the high-mass region of the spectrum. Low signal intensity of high mass ($m/z > 400$–500) organic ions is a serious drawback of ToF-SIMS. Discovery cluster

ion sources (Au_3^+, Bi_3^+, SF_5^+, C_{60}^+) allowed to enhance signal intensity [5], because these primary ions open the potential for higher yields of large molecules. Sample modification is an alternative approach. Matrix-enhanced SIMS and metal-assisted SIMS allow to amplify TOF-SIMS signal intensity by organic matrix or metal deposition [6,7]. Metal nanoparticle deposition, which increases TOF-SIMS secondary ion yields of polymer molecules [8], involves exposing the sample surface to a solution of citrate-capped Ag or Au nanoparticles. As a polymer incorporates a submonolayer amount of the particles at the surface, the ToF-SIMS signals become meaningfully enhanced [9–13]. Recently the enhancement of the SIMS signal has been reported for the self-assembled layers of Au nanoparticles (AuNPs) with peptides [14,15] and for *E. coli* bacteria cell with ZnO NPs [16].

The aim of the present work is to compare the effect of different nanoparticles on the SIMS signal from thin lipid layer deposited on the self-assembles layer of nanoparticles at the silicon wafer. We report the enhancement effect of lipid molecular ion yield when particle size and material is varied: (a) metallic Ag, Au and Pb NPs; (b) oxides SiO_2 and TiO_2; (c) core–shell Au/SiO_2 NPs and Au nanoclusters photodeposited on the TiO_2 nanoparticles.

2. Materials and methods

2.1. Materials

All descriptions of water below are referred to distilled water. Hydroxylamine hydrochloride $NH_2OH \cdot HCl$, sodium hydroxide

NaOH, silver nitrate $AgNO_3$, $HAuCl_4 \cdot 3H_2O$, lead acetate (II) $Pb(Ac)_2 \cdot 3H_2O$, sodium citrate Na_3Cit, sodium borohydride $NaBH_4$, octadecanethiol, tetraoctylammonium bromide, tetrapropoxysilane, were purchased from Aldrich (analytical grade). L-α-Phosphatidylcholine dioleoyl (1,2-dioleoyl-sn-glycero-3-phosphocholine, molecular weight – 786.11) was from Sigma–Aldrich. As TiO_2 nanoparticles the Aeroxide P25 were used. K_2CO_3, formaldehyde, toluene were purchased from Acros chemicals. Silicon wafers were from J&J Co., South Korea.

2.2. Nanoparticles synthesis

2.2.1. AuNPs type I

AuNPs were synthesized by citrate methods [17]. $HAuCl_4$ solution of 0.2 M was prepared. 1 mL $HAuCl_4$ solution was added to 94 mL water with stirring. The solution was heated to boiling with a hemisphere heating mantle under vigorous magnetic stirring. After boiling for 2 min, sodium citrate (353 mg) was rapidly added to the flask. The solution gradually turned gray–blue–crimson within a few minutes, indicating the formation of Au nanoparticles. The solution was kept boiling for additional 23 min. After that, the heating mantle was removed, and the solution was allowed to cool. The average particle size according to scanning electron microscope (SEM) measurements was 30 nm.

2.2.2. AuNPs type II

Gold particles were synthesized by a two-phase synthesis method [18], with some modifications at temperature of 23 °C. Tetraoctylammonium bromide solution in toluene (0.06 M, 35 mL) was added to $HAuCl_4$ solution (0.03 M, 15 mL), followed by stirring. Noticeable color manifested all $HAuCl_4$ transition in the organic phase. Octadecanethiol (0.44 mM) was added. It served as the stabilizer of the nanoparticles in the organic phase. A freshly prepared solution of sodium borohydride (0.4 M, 12.5 mL) was slowly added dropwise to the reaction mixture under vigorous stirring continued for other 3 h. The organic phase separated and evaporated on a rotary evaporator to a volume of 10 mL. The octadecanethiol excess was removed by several cycles with toluene–isopropanol sedimentation centrifuge. The resulting precipitate was dissolved in 20 mL of chloroform. The NPs average size was 5 nm.

2.2.3. AgNPs type I

$AgNO_3$ was preliminarily dissolved in water (0.01 M). $NH_2OH \cdot HCl$ (12 mg), 1 M NaOH (0.33 mL), $AgNO_3$ solution (11 mL) were successively added with stirring to 100 mL of water. The solution was stirred for 2 h at a room temperature of 23 °C. As a result, the gray opalescent solution was obtained. The average particle size according to SEM (scanning electron microscope) measurements was 80 nm [19].

2.2.4. AgNPs type II

The kind of sodium citrate reduction method was applied. Briefly, $AgNO_3$ 17 mg was preliminarily dissolved in water 100 mL. The solution was heated to boiling under vigorous magnetic stirring. Solution 4 mL of sodium citrate 1% was rapidly added to the flask. The reaction mixture is reflux during 30 min. The gray turbid solution was obtained. The NPs average size was 23 nm.

2.2.5. AgNPs type III

Method sodium borohydride reduction has been used [20]. Two solutions sodium citrate 0.4 mM in 50 mL water and silver nitrate 0.4 mM in 50 mL water were prepared and cooled in an ice bath. Sodium borohydride solution (25 mM) were prepared in water and kept in ice bath. The silver nitrate and sodium citrate solutions were mixed together in a conical flask and vigorously magnetic stirred. Then, 30 μL of the sodium borohydrite solution was added at once.

After 10 min of stirring, the solution was heated slowly without boiling and heated at near-boiling temperature of 90 °C for a further 90 min. The solution was cooled to room temperature with stirring. Color was eventually yellow–brown opalescent. The average size of NPs was 5 nm.

2.2.6. PbNPs

To 10 mL of water was added with stirring 1.8 mg of $Pb(Ac)_2 \cdot 3H_2O$, Na_3Cit_3, 1 mg and freshly prepared 0.1 M $NaBH_4$ solution of 4 mL. The solution was stirred under heating for 2 h. The color of the solution was white opalescent. The average particle size according to SEM was 30 nm.

2.2.7. Au/TiO2

The deposition of Au nanoparticles on TiO_2 nanoparticles was realized by photocatalytic reduction of Au^{3+} ions in aqueous TiO_2 suspension with methanol addition at 23 °C [21]. UV-A (Philips) operating at 362 ± 10 nm with power of 8 W was used for TiO_2 nanoparticles excitation and Au^{3+} ions reduction. The light flux was 6.9 mW/cm^2 and the exposition was 20 min. Methanol was used as an effective hole scavenger. The morphology of the particles was a TiO_2 core with a diameter of 20 nm with adjacent gold particles sized 5 nm according to the TEM.

2.2.8. SiO2NPs and core–shell Au/SiO2NPs

Synthesis includes a sequence of several stages: (1) preparation of spherical SiO_2 particles with a narrow size distribution; (2) chemical modification of the SiO_2 surface by amino groups; (3) synthesis seed gold nanoparticles; (4) binding seed gold nanoparticles to the surface of amino groups; (5) growth of continuous gold shell on the particle surface. Synthesis temperature was 23 °C. SiO_2 core synthesis: therefore, into 6 mL of isopropanol containing 0.77 mL aqueous ammonia solution (25%) there was added dropwise 0.42 mL tetrapropoxysilane $(C_3H_7O)_4Si$, magnetically stirred for 2 h and standing overnight. The product was washed twice by centrifuging in ethanol at 3000 min^{-1} and was reslurried in 6 mL of isopropanol. Spherical silica particles of 460 nm were formed. The SiO_2 nanoparticles of 250 nm were synthesized in similar manner with different precursor concentrations. This technique gives a fairly narrow particle size distribution. These silica particles were functionalized by 3-aminopropyl-triethoxysilane (APTES). Tetra-hydroxymethyl phosphonium chloride (THPC) was used as a reducer to prepare 2–3 nm Au seed nanoparticles. 0.1 mL of SiO_2/APTES suspension was mixed with 20 mL of THPC gold colloid, followed by 4 h stirring and held for days. The precipitate was washed twice with water and redispersed in 5 mL of water. To initiate the growth of the gold shell, the precursor silica particles covered with the small gold clusters were added to the aged $HAuCl_4$/K_2CO_3 solution. The ratio of the amount of the precursor particles added to the volume of the gold salt solution depended on the intended thickness of the gold shells. It was calculated assuming all added $HAuCl_4$ would reduce to gold shells around the silica. 37% formaldehyde was used as a reducer [22,23]. In the present work SiO_2 and Au/SiO_2 NPs were sensitized with diameter of SiO_2 core $D = 250$ nm and $D = 518$ nm, the Au shell layer was about 20 nm.

2.3. Sample preparation

L-α-Phosphatidylcholine dioleoyl (DOPC) solution in ethanol (600 mM) was used for the preparation of lipid films on a silicon wafer surface. To prepare control samples 25 μL of lipid solution was deposited on a silicon wafer and then dried under argon. For sample preparation a 50 μL NPs suspension (~100 ppm) was dropped on a wafer and dried under argon. After that 25 μL of lipid