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Exploration of the specific structural characteristics of thiol-modified single-stranded DNA self-assembled monolayers on gold by a simple model

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ABSTRACT

This paper proposed a simple hexagonal model to explore the specific structural characteristics of thiol-modified single-stranded DNA (ss-DNA) self-assembled monolayers (SAMs) on gold substrate. The calibrated gyration diameter d'_g ($d'_g = rd_g$) was used to quantify the size of ss-DNA molecules on gold by introducing a calibrating factor r, where d_g was ss-DNA gyration diameter in solution. Based on the model, the interfacial parameters of ss-DNA-SAMs on gold assembled under different ionic strength were obtained theoretically. The ss-DNA-SAMs were assembled on gold under different concentrations of C_{NaCl} and six important electrochemical parameters were used to validate the model experimentally, which include surface coverage (Γ_m), interfacial capacitance (C), phase angle ($\Phi_{1\,Hz}$), ions transfer resistance (R^*_{it}), current density difference (Δj) and charge transfer resistance (R_{ct}) from chronocoulometry (*CC*), cyclic voltammetry (*CV*) and electrochemical impedance spectroscopy (*EIS*). Three main aspects were included in this paper: (1) construction of a simple hexagonal model to describe the specific structural characteristics of ss-DNA-SAMs on gold; (2) calculation of the calibrating factor r by *CC* experiments and several important conclusions from the simple model; and (3) confirmation of the simple model by our experimental results and literature reports. The simple model may provide an important reference for optimizing the design of DNA sensor.

1. Introduction

Modification of thiol-modified single-stranded DNA (ss-DNA) self-assembled monolayers (SAMs) on gold substrate has been widely applied for DNA sensor (Arinaga et al., 2007; Castelino et al., 2005; Keighley et al., 2008; Mearns et al., 2006; Milkani et al., 2010; Peeters et al., 2008; Peterson et al., 2001,2002; Phares et al., 2009; Stachowiak et al., 2006; Wong et al., 2005). Surface structure of ss-DNA-SAMs on gold determines DNA-sensor's performances, e.g., sensitivity, detection limit, hybridization efficiency (H_E) and hybridization density (H_D). Table S1 indicates that the detection limit of ss-DNA-SAMs' hybridization can change from nM to fM with sensitivity from 10^6 to 10^{10} $\mu A\,cm^{-2}\,M^{-1}$. These factors, such as cations' concentration and types, substrate potential, mixed thiols, the spacer linking ss-DNA with gold, bases sequence and amount, would influence the surface structure of ss-DNA-SAMs on gold and consequently DNA-sensor's performances greatly. For example, Peeters et al. compare the effect of spaces (C_6 and C_{11}) on the H_E of mixed ss-DNA/alkanethiol SAMs and find that ss-DNA-SAMs with C_{11} space can improve the sensitivity, detection limit as well as the reproducibility (Peeters et al., 2008); Dharuman and Hahn obtain that ternary mixed monolayers of ss-DNA/thiols can enhance the hybridization effect than the conventional binary mixed monolayers of ss-DNA/thiols (Dharuman and Hahn, 2008; Dharuman et al., 2010). Although many techniques including scanning tunneling microscopy (STM) (Wackerbarth et al., 2004a,b), atomic force microscopy (AFM) (Legay et al., 2005), surface plasmon resonance (SPR) (Peterlinz et al., 1997), X-ray photoelectron spectroscopy (XPS) (Herne and Tarlov, 1997), neutron reflectivity (NR) (Levicky et al., 1998), fluorescence (Rant et al., 2004) and electrochemical methods (Ge et al., 2007; Steel et al., 1998) have been used to explore surface structure characteristics of ss-DNA-SAMs on gold (Table S2), there are still some fundamental questions unsolved, e.g., how to quantitatively describe the configuration of ss-DNA-SAMs on gold substrate? How about the relationships of DNA configuration with ions penetration and charge transfer inside ss-DNA-SAMs? What is the internal relationship of the structural characteristics of ss-DNA-SAMs on gold with H_E and H_D in DNA sensor study?

In order to explore the above questions, in this work, we proposed a simple model to describe the specific structural characteristics of ss-DNA-SAMs on gold. The calibrated gyration diameter d'_g ($d'_g = rd_g$) was used to quantify the size of ss-DNA molecules on

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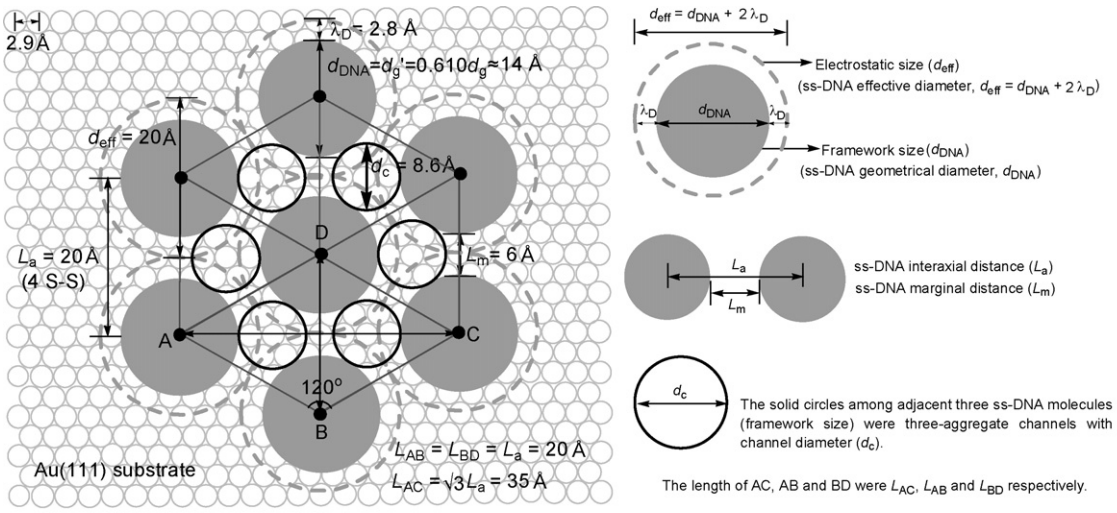
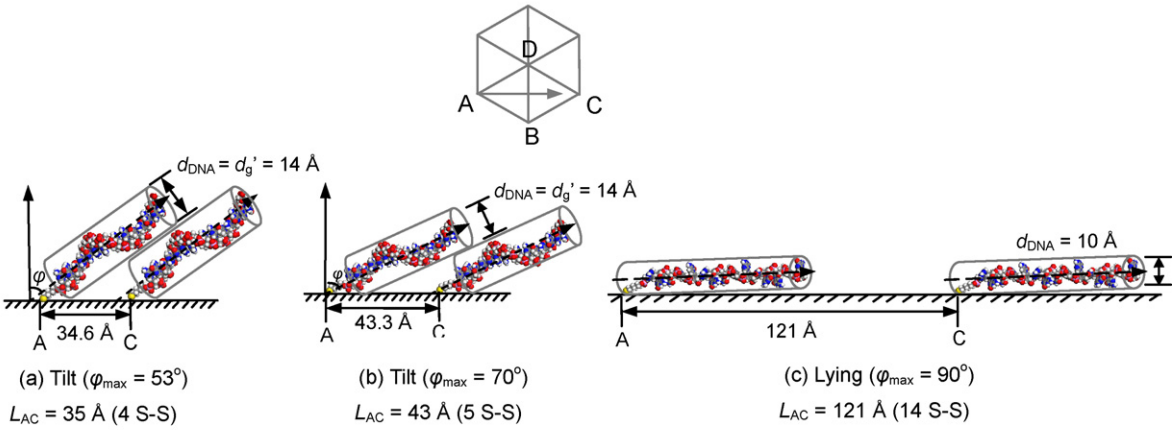


(A) Simple model of ss-DNA-SAMs with hexagonal packing on Au(111) when assembled under C_{NaCl} = 1.2 M with tilted angle φ (0°).



(B) The configurations of ss-DNA-SAMs on Au(111) when assembled under different C_{NaCl}

Fig. 1. (A) Simple model of ss-DNA-SAMs (HS-$(CH_2)_6$-5′-AGT ACA GTC ATC GCG-3′, 15 bases) on Au(1 1 1) with hexagonal packing (tilted angle $\varphi = 0°$). The ss-DNA-SAMs assembled under the concentration 1.2 M of a symmetric monovalent electrolyte with L_a = 20 Å (4S–S) was illustrated in this figure and ss-DNA-SAMs assembled under different concentrations with $L_a = n$S–S (n = 4, 5, 6, . . .) were shown at Figure S5; (B) the configurations of ss-DNA-SAMs assembled under different concentrations (a, 1.2 M; b, 0.33 M; and c, 0.01 M) on Au(1 1 1) with the maximal tilted angle φ_{max} (53°, 70° and 90°). The arrow in the small hexagon indicated the tilted direction (towards AC position) of ss-DNA molecules. The φ_{max} was obtained usually in the presence of strong electrostatic attraction between gold substrate and ss-DNA molecules.

gold by introducing a calibrating factor r. The model was validated by our experimental results and literature reports.

2. Experimental

2.1. Chemicals and apparatus

Thiol-modified single-stranded DNA (HS-$(CH_2)_6$-5′-AGT ACA GTC ATC GCG-3′) was purchased from Takara biotechnology (Dalian) Co. Ltd. Potassium hexacyanoferrate (III) ($K_3Fe(CN)_6$, 99%, Sigma), Potassium ferrocyanide trihydrate ($K_4Fe(CN)_6{\cdot}3H_2O$, ≥99%, ACROS), Sodium phosphate monobasic (NaH_2PO_4, ≥99%, Fluka), Sodium phosphate dibasic (Na_2HPO_4, ≥99.5%, Fluka), Sodium chloride (NaCl, ≥99%, Alfa), Tris(hydroxymethyl)nomethane (≥99.8%, Sigma–Aldrich). The CHI-660B electrochemical workstation (CH Instruments, USA) was used to perform electrochemical experiment. A three-electrode cell was applied, with a ss-DNA modified gold as working electrode, a large-area platinum foil as counter electrode and a saturated calomel (SCE) as reference electrode. The temperature was controlled at 25 ± 1 °C by the CS-501SP super digital thermostat bath (Huida Experimental Equipment Ltd., Chongqing, China).

2.2. Preparation of ss-DNA-SAMs and electrochemical characterization

Using our previous method (Li et al., 2010), polycrystalline gold electrodes (2.0 mm diameter, CH Instruments) were pretreated in turn: polished with alumina slurries, rinsed with water, dipped into piranha solution, sonicated in water, and electrochemical cleaning from −0.4 to +1.5 V in 0.5 M H_2SO_4 at 0.1 V s^{-1}. The real surface area (A) of gold electrodes was determined from the reduction charge of gold oxide with 400 μC cm^{-2} as a monolayer of chemisorbed oxygen. The roughness factor of gold electrodes R_f was 1.3 ± 0.2 ($R_f = A/A'$, A' was the geometrical area of gold electrode, 0.0314 cm^2). The pretreated gold electrodes were immersed into 10 μM ss-DNA