Extended Abstracts of the 2012 International Conference on Solid State Devices and Materials, Kyoto, 2012, pp1105-1106

Controlling Macroscopic Lipid Bilayer Self-Spreading by Molecule Gate Modulation in a Nanometer-Scale Gap

Yoshiaki Kashimura, Kazuaki Furukawa and Keiichi Torimitsu

NTT Basic Research Laboratories, NTT Corporation
3-1 Morinosato Wakamiya, Atsugi, Kanagawa 243-0198, Japan
Phone: +81-46-240-3548 E-mail: kashimura.yoshiaki@lab.ntt.co.jp

1. Introduction

Supported lipid bilayers (SLBs) are regarded as a model for cell membranes because they maintain many of the properties of a cell membrane such as lateral fluidity, and can reconstitute membrane proteins. Since SLBs can be formed on solid surfaces, they have attracted a lot of attention for use as an interface between semiconducting devices and biomolecules, as well as for their fundamental scientific interest [1]. The fabrication and handling of SLBs are of considerable importance if we are to achieve biodevice applications.

SLBs are generally prepared by the vesicle fusion method, which involves the adsorpton and consecutive rupture of small unilamellar lipid vesicles [2]. Instead of the vesicle fusion method, we employ the self-spreading method, which originates in the spontaneous growing nature of an SLB at a solid-liquid interface [3]. This method allows the dynamic handling of a macroscopic SLB, which is difficult to realize with the vesicle fusion method. Using the self-spreading technique, we achieved the spatial control of SLB formation on a micropatterned surface [4]. We also investigated the dynamics of an SLB passing through a nanometer-scale gap (nanogap) [5]. Furthermore, we recently reported that the SLB development could be switched on/off electrostatically by applying an electric field between nanogap electrodes [6]. In this study, we aimed at the precise control of SLB self-spreading, not simple on/off switching.

2. Experimental procedure

Figure 1 shows a schematic diagram of the device we used in this study. A pair of gold nanogap electrodes was fabricated on a SiO_2 surface. A 10 μm wide microchannel with wells at both ends was fabricated on the nanogap structure using an organic photoresist.

A lipid mixture was prepared consisting of L-α-phosphatidylcholine and L-α-phosphatidylglycerol (molar ratio 7:3) containing fluorescent probes (1 mol% Texas Red-DHPE). A small amount of the solid was attached to one of the wells. Self-spreading was initiated by immersing the device gently in a solution including 10 mM NaCl. Fluorescence from the SLB spreading along the microchannel was observed with a confocal laser scanning microscope (LSM). A DC voltage was applied between the nanogap electrodes. All the observations were performed in a NaCl solution at room temperature.

3. Results and Discussion

Figure 2 shows time-lapse LSM images of SLB self-spreading induced by an applied voltage modulation using a 5 nm nanogap. A red fluorescent SLB developed along a microchannel from the left side. Before the SLB passed through the nanogap, the applied voltage (V) had no effect on the self-spreading behavior [Fig. 2(a) and (b)]. When the SLB reached the nanogap, the self-spreading was halted by the application of -100 mV [Fig. 2(c)]. This situation was maintained at a reduced V value of -50 mV [Fig. 2(d)]. However, the SLB started to develop again when the applied voltage was reduced to less than -10 mV [Fig. 2(f)-(i)].

The above trapping/detrapping of the SLB self-spreading is almost the same as that described in our previous report [6], and has never been observed for the devices with a >15 nm nanogap. This is explained by the electrostatic trapping of the SLB by a very strong electric field (typically ~10^5 V/cm), where the electric double layer plays a crucial role. When we apply a voltage between nanogap electrodes, the effects of an electric field on a self-spreading SLB can be divided into two types depending on the relationship between the nanogap spacing (d) and the thickness of the electric double layer (D) which is mainly governed by the ionic concentration ($D \approx 3$ nm in 10 mM NaCl solution). The mechanism is illustrated in Fig. 3. When $d \gg D$, there is no significant change in the self-spreading because the electric field is shielded by counterions outside the electric double layers. In contrast, when $d \approx D$, the electric field is effectively applied over the nanogap as a result of the overlap of the electric double layers, which leads to the electrostatic trapping of the SLB. When we take account of the thermodynamics at a single molecule level, this phenomenon results from the competition between the electrostatic force and the Brownian motion (lateral diffusion) within an SLB, which is expressed as $2k_BT = qEd_B$ (eq. 1), where k_B is the Boltzmann constant, T is absolute temperature, q is the charge of a lipid molecule, E is the maximum electric field, and d_B is the amplitude of the Brownian motion. If we employ a sufficiently large E, we can obtain a small d_B so that a molecule is confined within a nanogap. Thus, the nanogap works as a molecule gate. According to eq. 1, the trapping/detrapping events of SLB self-spreading should be controlled by electric field modulation under a constant ionic concentration that satisfies $d \approx D$.

Next we focus on the spreading velocity. Figure 4(a) shows the double logarithmic plot of the spreading velocity (v) as a function of time (t). The voltage modulation record

is also shown. In general, the spreading velocity and time are known to satisfy the spreading equation, $v = (\beta/t)^{1/2}$, where β is the kinetic spreading coefficient, when an SLB grows on a solid surface [3]. We found that the device used here follows this relationship because we can draw lines with a slope of -0.5 at each applied voltage. The voltage modulation seems to affect the intercept, namely β, which maintains a slope of -0.5. We estimated the kinetic spreading coefficient at each applied electric field as shown in Fig. 4(b). As the applied electric field increases, the kinetic spreading coefficient decreases stepwise. With a lower electric field, we presume a linear relationship as depicted by the dotted line because the energy of a molecule is proportional to the electric field strength. From this result, the threshold electric field (E_{th}) is estimated to be ~ 3×10^4 V/cm. When the electric field is larger than E_{th}, the SLB remains trapped. Below E_{th}, SLB self-spreading proceeds and the spreading velocity increases with a reduction in the electric field strength.

Considering eq. 1, we can obtain $d_B \approx 15$ nm under the threshold condition. This is reasonable when we consider the fact that the typical width of nanogap electrodes (d_w, inset in Fig. 4(b)) is about 10-20 nm.

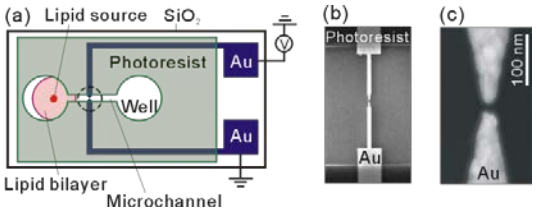

Fig. 1 (a) Schematic diagram of the device. (b) SEM image of the device around a nanogap. (c) SEM image of a nanogap.

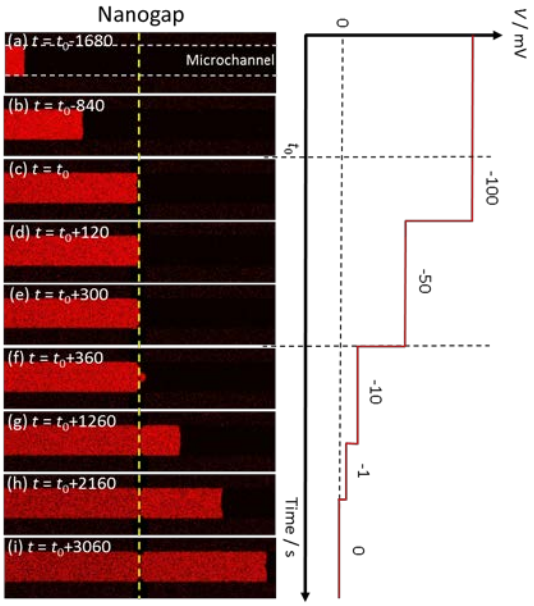

Fig. 2 Time-lapse images of a self-spreading SLB induced by the applied voltage modulation. A 5 nm nanogap and 10 mM NaCl solution were used. The red areas are the fluorescence from the SLB. A record of the voltage application is shown on the right. The time at which the advancing SLB reaches the nanogap is set at $t = t_0$.

4. Conclusion

We have demonstrated the fine-tuning of SLB self-spreading, not simple on/off switching, by employing molecule gate modulation using a nanogap. The technique and concept described here can provide a new methodology for the transport, detection and examination of biomolecules such as DNA sequencing.

Acknowledgement

This work was supported by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (20310076).

References

[1] E. Sackmann, Science, **271** (1996) 43.
[2] J. Salafsky, J. T. Groves, and S. G. Boxer: Biochemistry **35** (1996) 14773.
[3] J. Rädler, H. Strey, and E. Sackmann, Langmuir, **11** (1995) 4539.
[4] K. Furukawa, H. Nakashima, Y. Kashimura and K. Torimitsu, Lab Chip, **6** (2006) 1001.
[5] Y. Kashimura, J. Durao, K. Furukawa and K. Torimitsu, Jpn. J. Appl. Phys., **47** (2008) 3248.
[6] Y. Kashimura, K. Furukawa and K. Torimitsu, J. Am. Chem. Soc., **133** (2011) 6118.

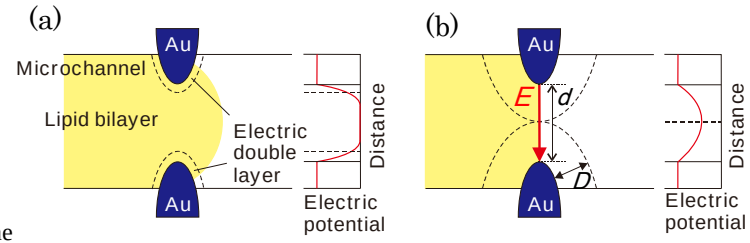

Fig. 3 Mechanism of electrostatic control of a self-spreading SLB. (a) $d \gg D$. (b) $d \approx D$.

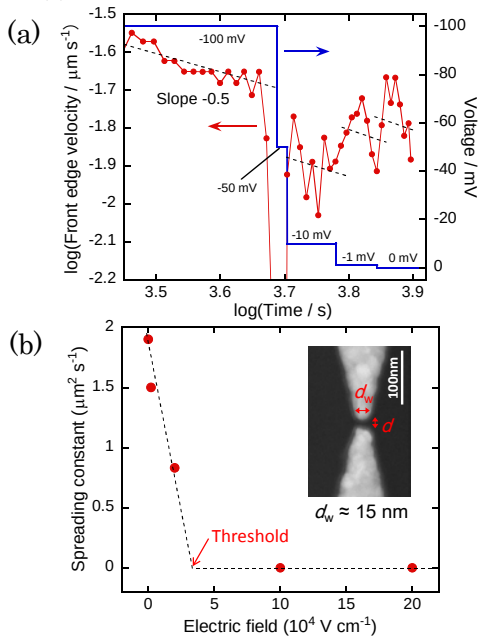

Fig. 4 (a) Double logarithmic plot of the spreading velocity (red) as a function of time. The voltage modulation record is also shown (blue). The dotted lines show a slope of -0.5. (b) The kinetic spreading coefficient for each applied electric field.