

Assembly of Highly Aligned DNA Strands onto Si Chips

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This paper reports a robust and efficient approach to assemble highly aligned DNA strands onto Si chips. The method combines advantages from molecular combing and microcontact printing to realize controlling both the density and direction of DNA strands on the Si chip. In addition, it also can be utilized to prepare stretched DNA structures on solid surfaces. Compared to approaches that use molecular combing directly on silanated surfaces, the stretched single-chain DNA structures are straighter. Furthermore, by exploiting the hydrophobic property of the intrinsic poly(dimethylsiloxane) stamp, this study also describes a simple way to produce straight bundled DNA arrays on Si and other substrates.

Introduction

Enormous progress has been made in utilizing DNA either for controlled self-assembly of molecularly designed nanostructures or as templates or scaffolds for engineered nanostructures.^{1–11} We have also successfully fabricated isolated polyaniline nanowires on Si surfaces by using aligned and immobilized DNA as growing templates.¹² The density and the position of DNA strands immobilized on the Si surfaces predetermined the density and the position, and even the orientation, of the polyaniline nanowires. However, to realize the full potential of the DNA-based nanotechnology for mass production of high-density functional nanodevices, it is essential to integrate individual DNA strands or specific DNA structures onto highly integrated Si circuits. To accomplish this, DNA needs to be stretched across electrode gaps and anchored onto selected electrodes on Si circuits. Previous efforts relied on dielectrophoresis^{13,14} or self-assembly guided by specially designed molecular recognition.^{5,15} These were time-consuming and still suffered from low efficiency. Molecular combing is well-known to stretch and align DNA molecules onto solid surfaces.^{16–18} A recent report by

Fritzsche et al.^{19,20} demonstrated that DNA strands could be positioned to an aminopropyl-triethoxysilane (APTES)-modified Si chip by direct molecular combing. This method sounds attractive because of its simplicity, but it suffers from a lack of location and direction configurability during combing as a result of the inherent limitation of the molecular combing technique.

In the present work, we demonstrate an efficient and robust method to assemble DNA or DNA–complex structures onto Si chips with precise location and direction control. The method combines *molecular combing and microcontact printing* (μ CP) techniques, taking advantages from both. Instead of printing thiol molecular “inks” onto Au films, as in the most common form of μ CP, the idea here is that stretched and aligned DNA strands are used as “ink” and printed onto Si chips, with controlled position and orientation. The DNA “ink” on the poly(dimethylsiloxane) (PDMS) “stamp” is stretched and aligned using a molecular combing technique. Considering that the μ CP has been used for wafer-scale pattern fabrication, the method reported here is potentially extendable to large-scale DNA integration and practical production of nanodevices.

The strategy for assembly of highly aligned DNA strands onto Si chips is illustrated schematically in Figure 1. (1) The molecular combing method is used to prepare parallel arrays of DNA strands on the PDMS stamp with controlled direction and density. (2) The Si chip is modified to be an amino-terminated surface. (3) The highly aligned DNA strands are transferred onto the pre-modified Si chips by bringing them into direct contact. By orienting the DNA/PDMS stamp in such a way that the stretched DNA is perpendicular to the gaps, the DNA strands will bridge the gaps on the Si chip.

μ CP has been widely used to pattern many materials (e.g., thiol molecules, proteins, nanoparticles, and metals).²¹ An important feature for an efficient printing requires that the interaction between the “ink” and the substrate surfaces is stronger than with the “stamp” PDMS surface, so that the “ink” can be transferred to the substrates during the contact procedure. Because the interaction between the PDMS surface and DNA is relatively weak and because we modify the Si chip surface to be terminated with amino groups so that DNA interacts

- (1) Seeman, N. C. *Acc. Chem. Res.* **1997**, *30*, 357.
- (2) Seeman, N. C. *Nature* **2003**, *421*, 427.
- (3) Yan, H.; Park, S. H.; Finkelstein, G.; Reif, J. H.; LaBean, T. H. *Science* **2003**, *301*, 1882–1885.
- (4) Mbindyo, J. K. N.; Reiss, B. D.; Martin, B. R.; Keating, C. D.; Natan, M. J.; Mallouk, T. E. *Adv. Mater.* **2001**, *13*, 249–254.
- (5) Braun, E.; Eichen, Y.; Sivan, U.; Ben-Yoseph, G. *Nature* **1998**, *391*, 775.
- (6) Keren, K.; Krueger, M.; Gilad, R.; Ben-Yoseph, G.; Sivan, U.; Braun, E. *Science* **2002**, *297*, 72–75.
- (7) Keren, K.; Berman, R. S.; Bushstab, E.; Sivan, U.; Braun, E. *Science* **2003**, *302*, 1380–1382.
- (8) Ford, W. E.; Harnack, O.; Yasuda, A.; Wessels, J. M. *Adv. Mater.* **2001**, *13*, 1793.
- (9) Richter, J. *Physica E* **2003**, *16*, 157.
- (10) Warner, M. G.; Hutchison, J. E. *Nat. Mater.* **2003**, *2*, 272.
- (11) Monson, C. F.; Woolley, A. T. *Nano Lett.* **2003**, *3*, 359.
- (12) Ma, Y. F.; Zhang, J. M.; Zhang, G. J.; He, H. X. *J. Am. Chem. Soc.* **2004**, *126*, 7097–7101.
- (13) Namasivayam, V.; Larson, R. G.; Burke, D. T.; Burns, M. A. *Anal. Chem.* **2002**, *74*, 3378.
- (14) Dewarrat, F.; Calame, M.; Schonenberger, C. *Single Mol.* **2002**, *3*, 189.
- (15) Holzel, R.; Gajovic-Eichelmann, N.; Bier, F. F. *Biosens. Bioelectron.* **2003**, *18*, 555.
- (16) Bensimon, A.; Simon, A.; Chiffaudel, A.; Croquette, V.; Heslot, F.; Bensimon, D. *Science* **1994**, *265*, 2096.
- (17) Bensimon, D.; Simon, A. J.; Croquette, V.; Bensimon, A. *Phys. Rev. Lett.* **1995**, *74*, 4754.
- (18) Michalet, X.; Ekong, R.; Fougereuse, F.; Rousseaux, S.; Schurra, C.; Hornigold, N.; van Slegtenhorst, M.; Wolfe, J.; Povey, S.; Beckmann, J. S.; Bensimon, A. *Science* **1997**, *277*, 1518.

(19) Maubach, G.; Csaki, A.; Born, D.; Fritzsche, W. *Nanotechnology* **2003**, *14*, 546–550.

(20) Maubach, G.; Fritzsche, W. *Nano Lett.* **2004**, *4*, 607–611.

(21) Xia, Y. *Adv. Mater.* **2004**, *16*, 1245–1246.

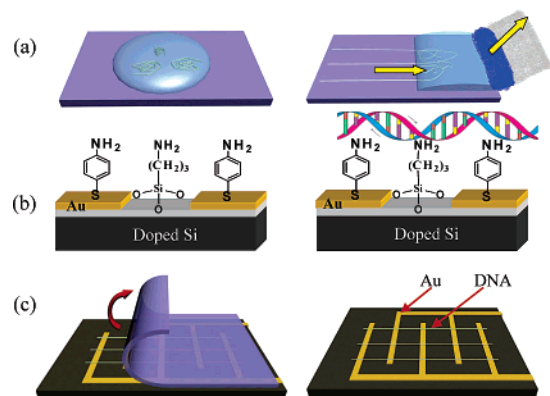


Figure 1. Schematic drawing showing the procedures to integrate DNA strands onto Si chips. (a) Molecular combing to “ink” a PDMS stamp with aligned DNA strands using a piece of filter paper. (b) Modifying the Si chip to have an amino-terminated surface to firmly anchor the DNA strands. (c) Transferring the aligned DNA strands from PDMS to the Si chip by contact printing.

stronger with the Si chip, transferring DNA strands from the PDMS “stamp” to the Si chip should be a straightforward procedure. Evidence to support this point was shown in a recent report from Nakao’s group.²² To control the location and direction of the “ink” (here, the stretched DNA strands) onto the substrate is routine for the μ CP technique. Large-area printing and multilayer printing with good registration have been reported.^{23,24} Therefore, the key procedure to integrate DNA onto Si chips with controlled direction and density is to put the right “ink” onto the PDMS stamp, that is, to stretch and align DNA strands onto the PDMS stamp with density and direction control. To establish this, our initial experiments were conducted on PDMS, and the aligned DNA strands were transferred to oxidized Si substrates pre-modified with APTES for atomic force microscopic imaging.

Experiments

Molecular Combing. Molecular combing is widely used to stretch and immobilize DNA strands onto a solid surface. During the combing process (Figure 1a), the air–water interface exerts a local force on the molecules perpendicular to the liquid front. After the motion of the meniscus, which is generated by evaporation of a DNA-containing solution on the substrate, the molecules lie on the surface stretched and aligned perpendicular to the contact line. The receding of the meniscus caused by the evaporation of the DNA solution on the surface can be accelerated in several ways. The first molecular combing work to achieve the moving meniscus was accomplished by sliding two pieces of glass with a drop of DNA solution sandwiched between them.¹⁶ Modified versions include using a Langmuir–Blodgett (LB) setup,¹⁸ mechanical moving,²⁵ pipet sucking,²⁶ and N_2 blowing.²⁷ In this work, a piece of filter paper is used to control the speed of the meniscus movement. Compared to the LB setup, a very small amount of DNA solution is used and efficiency is achieved similar to that of more complicated mechanical setups. In the

(22) Nakao, H.; Gad, M.; Sugiyama, S.; Ohtobe, K.; Ohtani, T. *J. Am. Chem. Soc.* **2003**, *125*, 7162.

(23) Xia, Y.; Whitesides, G. M. *Angew. Chem., Int. Ed.* **1998**, *37*, 550–575.

(24) Michel, B.; Bernard, A.; Bietsch, A.; Delamarche, E.; Geissler, M.; Juncker, D.; Kind, H.; Renault, J.-P.; Rothuizen, H.; Schmid, H.; Schmidt-Winkel, P.; Stutz, R.; Wolf, H. *IBM J. Res. Dev.* **2001**, *45*, 697–719.

(25) Yokota, H.; Johnson, F.; Lu, H.; Robinson, R. M.; Belu, A. M.; Garrison, M. D.; Ratner, B. D.; Trask, B. J.; Miller, D. L. *Nucleic Acids Res.* **1997**, *25*, 1064.

(26) Nakao, H.; Hayashi, H.; Yoshino, T.; Sugiyama, S.; Ohtobe, K.; Ohtani, T. *Nano Lett.* **2002**, *2*, 475–479.

(27) Deng, Z.; Mao, C. *Nano Lett.* **2003**, *3*, 1545–1548.

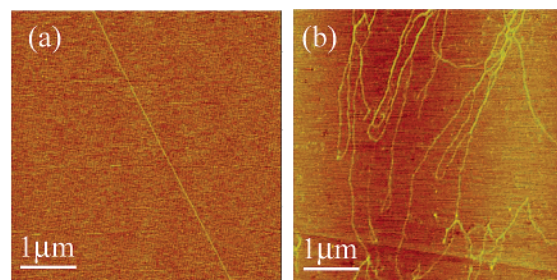


Figure 2. Tapping mode AFM images of DNA strands on APTES-modified Si surfaces prepared by combined molecular combing and contact printing. (a) Intrinsic PDMS. (b) PDMS was treated with UV/O_3 for 30 s.

stretching process (Figure 1a), a 5- μ L drop of λ -DNA solution [New England Biolabs, 5 μ g/mL in TE buffer (10 mM Tris-HCl and 1 mM ethylenediaminetetraacetic acid, pH = 8.0)] was deposited on the PDMS sheet. After 3 min of incubation, the solution was adsorbed by a piece of filter paper with a pore diameter of 11 μ m from Whatman. In the process, the position of the filter paper was kept constant. Due to the intrinsic pore structures of the filter paper, it absorbed the DNA solution automatically. As a result, a moving meniscus was produced. During incubation, freely floating DNA molecules randomly bound to the PDMS surface by their extremities. When the drop was absorbed by the filter paper at a constant speed, the receding meniscus exerted a localized, constant force on the still coiled and immersed part of each of the anchored molecules, which were, thus, progressively uncoiled. The uncoiled part was stretched and irreversibly fixed on the dry region of the PDMS surface. The PDMS was rinsed with Nanopure water (Barnstead) and blown dry with N_2 in the filter paper attraction direction. Then the DNA strands were transferred by bringing the PDMS sheet into direct contact with an APTES-treated Si surface.²⁸

Atomic Force Microscope. The transferred DNA was imaged with a tapping mode atomic force microscope in ambient air (Nanoscope III A, Digital Instruments). During imaging, a 125- μ m-long rectangular Si cantilever/tip assembly was used with a spring constant of 40 N/m, resonance frequency of 315–352 kHz, and tip radius of 5–15 nm. The applied frequency was set on the lower side of the resonance frequency. The image is generated by the change in amplitude of the free oscillation of the cantilever as it interacts with the sample. The height differences on the surface are indicated by the color code: lighter regions indicate higher heights.

Results and Discussion

The intrinsic PDMS surface is very hydrophobic (the contact angle is around 120°). Therefore, the interaction between poly-ionic DNA strands and the hydrophobic PDMS surface is weak. In some cases, we get very straight DNA transferred on the Si surface but with very low density, less than 1 DNA strand/5 μ m² (Figure 2a). The height of the DNA strands is in the range of 0.3–0.4 nm, similar to the reported values.^{12,17,27,29} The DNA samples with low density are good for some applications, for example, as templates to grow nanowires. The resulting nanowires, in these cases, have been used as a model system to study single nanowire electronic properties.^{5,6} For some high-performance electronics, a large parallel array of nanowires is needed, so a higher DNA density may be preferred.³⁰

Treatment of the PDMS Stamp by UV/O_3 To Increase DNA Density. Our first thought to achieve good DNA alignment in combination with a large number

(28) Chaudhury, M. K.; Owen, M. J. *J. Phys. Chem. B* **1993**, *97*, 5722–5726.

(29) Dittmer, W. U.; Simmel, F. C. *Appl. Phys. Lett.* **2004**, *85*, 633–635.

(30) Duan, X. F.; Niu, C. M.; Sahi, V.; Chen, J.; Parce, J. W.; Empedocles, S.; Goldman, J. L. *Nature* **2003**, *425*, 274–278.

of DNA strands was to tune the surface property of PDMS. We treated the PDMS sheet with UV/O₃ cleaner (UVO-Cleaner, model 42, Jelight Company, Inc.) for different time periods. It was reported that these surface treatments resulted in a hydrophilic surface equipped with monolayer of -OH groups on the PDMS surfaces,^{31–33} which could increase the interaction with DNA strands, so that a higher density of DNA strands on the PDMS sheet by molecular combing was expected. Figure 2b shows an atomic force microscopy (AFM) image of DNA on the Si surface after a 30-s treatment and then the same procedures (molecular combing, μ CP, and AFM imaging) were performed as described above. We indeed observed more DNA strands transferred onto Si surfaces, but they were only partially stretched.

The force acting on the air–water interface to align DNA is mainly due to the surface tension, which can be described as¹⁶ $F \approx \pi\gamma D$, where γ is the surface tension and D is the diameter of the DNA strands. It was reported by Zisman^{34,35} that the surface tension of a liquid on a solid surface is a linear function of the variation of the cosine contact angle of the liquid on the surface. Therefore, the larger the contact angle, the stronger will be the combing force. The combing, however, is suppressed in the presence of strong interaction with the surface. The degree of the molecule's extension depends on both the surface tension and the interaction between DNA and the surface. The force exerted on the DNA molecules in solution results from a local competition between (1) the local action of the meniscus on the DNA molecules and (2) the local DNA/surface interaction at the meniscus (nonspecific adsorption).

Although UV/O₃ treatment of PDMS increased the interaction with DNA strands, which increased the density of the DNA on the surface, the treatment also decreased the contact angle of the DNA solution on this PDMS sheet and so the force to stretch DNA during combing. Therefore, the DNA strands were only partially stretched.

As the surface was treated with longer times, the contact angle became even smaller such that a thin liquid film remained after retraction of the DNA solution. With this PDMS sheet, we could not find any DNA transferred onto the Si surface (data not shown). It is possible that, due to the hydrophilic PDMS surface, the receding meniscus did not effectively speed up the evaporation of the DNA solution so that the DNA strands were not irreversibly anchored on the surface. Instead, they were washed away in the following water cleaning procedure. Another likely reason is that the enhanced interaction between -OH-terminated PDMS and DNA made the DNA tightly anchored to the PDMS surface and hard to transfer to the Si surface during contact printing.

Meniscus Speed Influences DNA Density. In the reported molecular combing works,^{18,25} varying the meniscus speed in the range of 300–500 $\mu\text{m/s}$ did not affect the population and the conformation of DNA molecules significantly. In our case, the moving meniscus can be fast as 5 mm/s when using a filter paper with a pore size of 11 μm to absorb the DNA solution. Considering that the interaction between the intrinsic PDMS surface and DNA is so weak, a fast-moving drop resulted in few strands

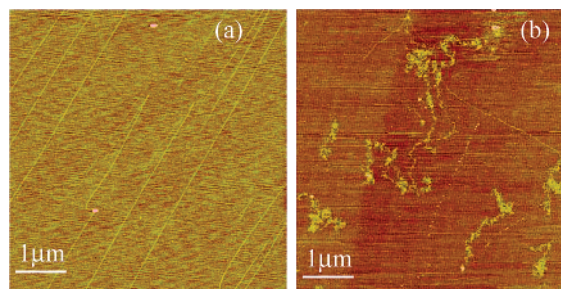


Figure 3. (a) Tapping-mode AFM images of DNA strands on APTES-modified Si surfaces prepared by combining molecular combing and contact printing. (a) Molecular combing using a piece of filter paper with a 3- μm diameter pore size; (b) molecular combing using a piece of Kimwipe paper.

of DNA, and in some cases no DNA attached on the surfaces at all.

Reducing the speed of the meniscus could improve the retention of DNA molecules on the surface. By changing the filter paper with a pore size of 3 μm , to reduce the absorption speed and, therefore, the receding meniscus speed (2 mm/s), we found that the density of DNA was greatly increased with retained straightness (Figure 3a). Further slowing down the absorption speed (250 $\mu\text{m/s}$) by using a piece of Kimwipe EX-L paper (Kimberly-Clark Corp.) resulted in more DNA strands left on the surface with a variety of conformations including some straightened molecules and many folded and irregularly coiled structures (Figure 3b).

The reason meniscus speed influences DNA density may come from the weak interaction between DNA and the intrinsic PDMS surface so that the hydrodynamic dragging force during combing may also play a role in the molecular combing process.^{36,37}

$$F_{\text{drag}} = \eta lV$$

where η is the liquid viscosity, l is the DNA length, and V is the velocity of the DNA drop. During incubation, multiple extremities along the DNA length are weakly adsorbed on the PDMS surface keeping a native coiled shape of the DNA strands. During combing, the velocity is so fast that the F_{drag} overcomes the interaction between the PDMS and DNA. The DNA strands will be removed away from the surface with the liquid drop resulting in a very low density of the DNA on the surface. When the velocity is slow, all the anchoring points along the DNA chain remain in place during combing, so that the DNA density increases while not being fully stretched. In an extreme case, if the DNA solution were not adsorbed, the meniscus speed would be zero in the center of the DNA drop and native coiled-shaped DNA strands would be left on the surface.³⁶

Using filter paper to control the moving speed of the DNA solution provides advantages of uniformity of the straightened molecules on the surface compared to using a pipet.^{22,26} The pipet method gives DNA strands that are stretched and aligned toward the center of the PDMS sheet. Furthermore, because the speed was controlled by the pore size of the filter paper without mechanical parts and human intervention, the filter paper method is simple and repeatable.

DNA Solution Concentration Influences both DNA Density and the Formation of Bundled DNA Struc-

(36) Abramchuk, S. S.; Khokhlov, A. R.; Iwataki, T.; Oana, H.; Yoshikawa, K. *Europhys. Lett.* **2001**, *55*, 294–300.

(37) Gerdes, S.; Ondarcuhu, T.; Cholet, S.; Joachim, C. *Europhys. Lett.* **1999**, *48*, 292–298.

(31) Chaudhury, M. K.; Owen, M. J. *J. Phys. Chem.* **1993**, *97*, 5722.

(32) Chaudhury, M. K.; Whitesides, G. M. *Science* **1992**, *255*, 1230–1232.

(33) Efimenko, K.; Wallace, W. E.; Genzer, J. *J. Colloid Interface Sci.* **2002**, *254*, 306–315.

(34) Semal, S.; Bauthier, C.; Voue, M.; Vanden Eynde, J. J.; Gouttebaron, R.; De Coninck, J. *J. Phys. Chem. B* **2000**, *104*, 6225–6232.

(35) Zisman, W. A. *Adv. Chem. Ser.* **1964**, *64*, 561.

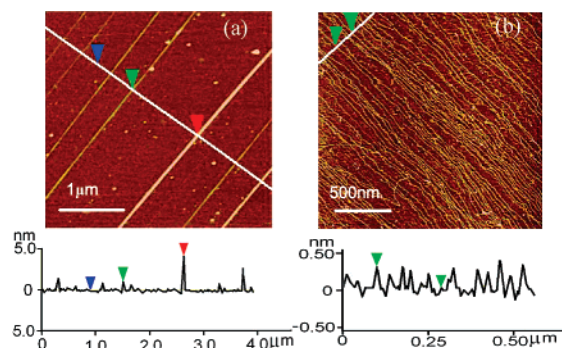


Figure 4. (a) Bundled DNA strands on an APTES-modified surface prepared by combining molecular combing and contact printing (DNA concentration = 25 $\mu\text{g}/\text{mL}$). (b) Using the same DNA solution, molecule combing was performed directly on an APTES-modified mica.

tures. To further increase the density, we also used higher concentrations of the DNA solution while using the filter paper with a pore size of 3 μm to keep the same flow speed of the drop. When the concentration was increased to 25 $\mu\text{g}/\text{mL}$, we found a very interesting phenomenon that DNA strands became bundled and aligned straight on the surface. Figure 4a shows an example of the bundled structures. The height of the highest DNA bundle in this image is around 4.8 nm, roughly corresponding to 17 DNA strands bundled together. A comparison experiment was performed by directly combing on APTES-modified mica surfaces. Instead of bundled DNA structures, individual DNA strands with a very high density were obtained (Figure 4b). The height of the individual DNA strands in this image is about 0.3–0.4 nm, similar to the single-chain DNA shown in Figure 2a.

The bundled DNA structures in many cases are desirable because they are mechanically stronger for further experiments, and also they can provide more binding and nucleation sites for fabrication of continuous nanowires when DNA is used as a growing template.²⁹ Although at this stage there are no theoretical models describing the effect of the surface on this behavior, we postulate that it is because the unfavorable interactions between the charged DNA strands and the very hydrophobic surface of PDMS results in relatively stronger DNA interchain interactions during the stretching process. It is known that a multivalent cation such as Mg^{2+} in DNA solutions can greatly enhance the DNA interchain interaction by forming a charge bridge between the negatively charged phosphate groups along the DNA backbone.³⁸ To demonstrate the hypothesis, we added 10 mM Mg^{2+} into the DNA solution to increase the DNA interchain interactions. We indeed found increased bundle structures after combing.

Using the combined *molecular combing and microcontact printing* approach, the orientation of the stretched DNA strands on the surface can be easily controlled simply by changing the contact printing angles after the DNA strands are aligned on the PDMS stamp. Figure 5a shows that a complex crossed DNA array was achieved with layer-by-layer contact printing by changing the contact directions in the sequential steps. We first aligned and immobilized DNA strands (DNA concentration, 25 $\mu\text{g}/\text{mL}$, a piece of filter paper with 3- μm -diameter pore size was used during molecular combing) onto the PDMS sheet and transferred them onto an APTES pretreated Si surface by contact printing. Then the second layer of aligned DNA

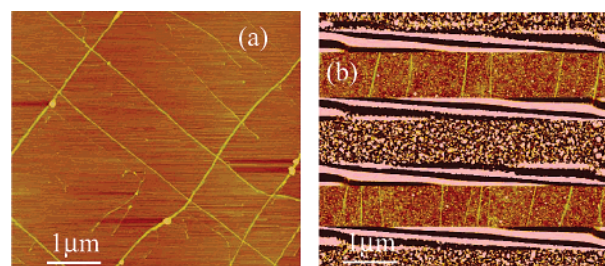


Figure 5. (a) DNA crossed structures prepared with layer-by-layer contact printing by changing the contact directions in the sequential steps. (b) DNA strands bridging the electrode gaps on Si chips by controlling the printing angle perpendicular to the facing electrode gaps.

strands was obtained by repeating the same procedures and controlling the contact printing direction perpendicular to the first layer of DNA strands.

The capability of aligning and transferring DNA strands with controlled density and direction onto the APTES-modified Si surface promises success in orientating and positioning DNA strands onto Si chips. The Si chip (here we used a simple interdigitated array of electrodes on Si chips fabricated by traditional photolithography to demonstrate the concept) was first treated by APTES to generate amino terminals over the silicon surface, followed by treatment with 4-aminothiophenol to place amino groups over the surfaces of the gold electrodes. The aminothiophenol was chosen for the electrode surface because the conjugation of the benzene ring will show less electrical resistance than the aliphatic chain of 2-aminoethanethiol (Figure 1b). This is important for further device fabrication or conductance measurements when using the bridged DNA as templates for metal, semiconductor, or even conducting polymer nanowires fabrication. Next, the DNA strands were stretched and aligned onto a PDMS stamp using filter paper with a pore size of 3 μm . Finally, transferring the aligned DNA strands by controlling the contact printing direction perpendicular to the facing microelectrode gaps resulted in DNA strands bridging across the electrode gaps on the Si chip, as shown in Figure 5b.

Conclusions

Our studies have delineated a facile and efficient approach to bridge DNA strands across electrode gaps on Si chips. Our ongoing work is to take full advantage of the concept of μCP ^{39–42} by designing PDMS stamps with appropriate raised patterns, so that DNA strands could be integrated precisely onto multiple locations on Si chips in one single printing. By changing the printing angles, the direction of DNA strands can match the angles of the electrodes on the chips. High-density and high-precision integration of DNA into Si chips, combined with DNA-templated nanofabrication techniques, should then enable DNA to be used in practical nanodevice fabrications.

In addition, this approach also offers several other benefits to prepare stretched DNA samples on solid substrates for some other applications. (1) The surface of the PDMS stamp is so hydrophobic that straight DNA wires are easy to achieve because of the large surface

(38) Bezanilla, M.; Manne, S.; Laney, D. E.; Lyubchenko, Y. L.; Hansma, H. G. *Langmuir* **1995**, *11*, 655–659.

(39) Jackman, R. J.; Wilbur, J. L.; Whitesides, G. M. *Science* **1995**, *269*, 664.

(40) Larsen, N. B.; Biebuyck, H.; Delamarche, E.; Michel, B. *J. Am. Chem. Soc.* **1997**, *119*, 3017.

(41) Libioulle, L.; Bietsch, A.; Schmid, H.; Michel, B.; Delamarche, E. *Langmuir* **1999**, *15*, 300.

(42) Delamarche, E.; Schmid, H.; Bietsch, A.; Larsen, N. B.; Rothuizen, H.; Michel, B.; Biebuyck, H. *J. Phys. Chem. B* **1998**, *102*, 3324.

tension, which is important when the DNA structures are used as templates to grow nanowires, and the latter is utilized as model systems to study single-wire electronic properties. (2) For the same reason, by simply adjusting the DNA concentration, we can controllably obtain straight bundled DNA structures. (3) Compared to the approach in which molecular combing was directly performed on silanated surfaces, the density and the straightness of DNA are more reproducibly controlled by our reliance on the hydrophobic surface property of the PDMS stamp. This is because the molecular combing process is very sensitive to the surface modification, and small variations in the surface coating affect the degree of DNA extension. The quality of the surface treatment by silanization

procedures is usually variable.¹⁶ As a result, the densities of anchored DNA molecules and their extension vary from batch to batch. Furthermore, even for the same batch of silanated substrates, the contact angle and the surface tension of the DNA solution is severely affected by humidity to the extent that the DNA combing results are influenced by weather. Our procedure for μ CP onto surfaces is, therefore, more reproducible and controllable than direct molecular combing of DNA onto solid substrates.

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