

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Based on fundamental chemistry, biotechnology and material science, people over past three decades have developed powerful disciplines and knowledge that allow the engineering of advanced and functional substances for application in highly integrated electronic, mechanical and optical nanodevices, sensors or catalysts. “Where Nature finishes producing its own species, man begins, using natural things and with the help of this nature, to create an infinity of species,” Nobel laureate Jean-Marie Lehn used these words to give an overlook of the future of highly interdisciplinary supramolecular chemistry [1]. Therefore, when using natural things to produce new substances for further application, it is very important to utilize their nature. For example, DNA primers originally are genetic substances that serve as the messenger to transfer genetic information from generation to generation. However, due to their highly specific recognition and self-assembly ability, DNA primers have become a powerful linker that makes spontaneous and effective connections between nanoclusters in engineering of nanostructure. Another significant property of nanotechnology is its “interdisciplinary nature”. As we can see in the Fig. 1.1, chemistry is the central science for the development of applied disciplines such as material science and biotechnology. Material science, which is based on classic chemical researches and engineering technologies, has led to enormous advanced modern materials, such as ceramics and, nanoclusters. Combined with tailored biomolecules, like proteins and, nucleic acids, we are able to develop future nanodevices composed of various advanced modern materials [1].

Nobel physicist, Richard Feynman, once pointed out more than 40 years ago, “There is

plenty of room at the bottom”, which best describes the central idea of nanotechnology [1]. The conventional *top-down processes* are always the main concepts in the development of human civilization. As human technology develops, people tend to fabricate more and more delicate tools or functional devices. However, this strategy will eventually reach a limit that people cannot easily go beyond based on available technologies, such as photolithography fabrication process. For example, the structural dimensions of computer microprocessors are currently on the range of about 90 nm, which is already the highest level of conventional top-down technology. In the foreseeable future, any further miniaturization process will lead to much more complicated problems such as quantum effect and power consumption, which will consequently cost much more effort to make a step to further miniaturization. As a result, it is reasonable and critical for people now to change the way we used to develop things from conventional *top-down processes* to *bottom-up processes*. This is the reason why Richard Feynman said prudently and presciently: there is plenty of room at the bottom. Compared to top-down processes, bottom-up processes concern the assembly of molecular and colloidal building blocks to produce larger (10~100 nm) and functional devices. The forces that make the assembly to happen are similar to those that involve in the interaction between molecules, such as hydrogen bonds, Coulombic force, and Van der Waals Force.

When talking about nanotechnology, it is referring to the size scale from 10 nm to 100 nm. As shown in Fig. 1.2, the conventional top-down processes can hardly construct structures smaller than 100 nm, while the bottom-up processes also reach a limit about 2~5 nm. Substances that are equal to or smaller than 2~5 nm are too small to be controllable and useful. Obviously, there is a gap that exists in the range about 10~100 nm and both biotechnology and material science naturally meet at the same length scale, which is about 5 nm to 200 nm. As a result, according to Christof M. Niemeyer [1], the two different compounds appear to be suited for addressing the gap: (1) biomolecular components, such as proteins and nucleic acids, and (2) colloidal nanoparticles comprised of metal and

semiconductor materials.

In sum, nanotechnology today is best characterized by its interdisciplinary study. The combination of advanced materials (like nanoclusters and ceramics) and tailored biomolecules (like nucleic acids and, proteins) will lead to the creation of future nanodevices. In the way to construct nanostructures, when conventional top-down processes, such as photolithography fabrication process, face more and more difficulty to get any further miniaturization, it is important for us to put more efforts on novel bottom-up assembly processes, such as DNA self-assembly. The forces that contribute to assembly processes are similar to those of the molecular interaction, such as hydrogen bonds, ionic interaction, and van der Waals force. According to Christof M. Niemeyer [1], the individual components that are able to be employed in the assembly processes should fulfill three basic requirement: (1) Intrinsic functionalities, such as optical, electronic, or catalytic property, are designed to allow the particular applications. (2) Modules need to be reprogrammable through their specific constitution, configuration, and conformation. (3) The building blocks need to have appropriate size to bridge the gap ranging from 10 nm to 100 nm. If we correctly choose the kinds of substances for assembly process and precisely control the interacting forces between the building blocks, we are able to construct the nanostructures for particular application.

1.2 REVIEW ON NANOPARTICLES

Among many nanoclusters for assembly process, inorganic nanoparticles (NPs) are the most attractive ones. The researches on the synthesis, characterization and applications of inorganic NPs have been increasing significantly in recent years. The advantages of inorganic NPs are shown as follow: (1) There has been many well developed synthesis methods of the NPs, which are often simple and cheap for large quantity preparation. (2) The NPs usually have interesting optical, electronic, and catalytic properties, which are quite

different from those of their corresponding bulk materials. Also, these properties depend strongly on the size of NPs, such as the superior size-dependent photoconductivity of CdSe NPs. (3) The NPs are very convenient to be conjugated with biomolecules by utilizing the intrinsic chemical nature of the surface on NPs. For example, the Au NPs can be easily conjugated to DNA primers through the formation Au-S bond. (4) The size of NPs, conventionally ranging from one to hundreds of nanometers, is particularly suitable for them to serve as building blocks for the assembly of larger nanostructures and contact closely with the micro systems, like the silicon chips.

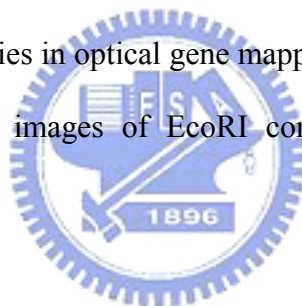
To begin with, we review some significant experiments about metal NPs. One of the first examples used proteins as the biomolecular recognition linkers to realize Ag-Au NPs networks, taking advantage of the interaction between antibodies and low molecular weight organic compounds, the so-called hapten groups [1]. The conceptual idea is illustrated in Fig. 1.3. In this experiment, Shenton et al. functionalized gold and silver NPs with immunoglobulins of class G and E (IgG and IgE), respectively. To make the cross-linking between functionalized Au NPs and construct the homo-oligomeric structure, mono-specific linkers that contained two terminal hapten groups were synthesized and added to the Au NPs suspension, as shown in Fig. 1.3(a). On the other hand, to construct the hetero-dimeric structure composed of Ag-Au NPs, bi-specific linkers were synthesized and added to the Au and Ag NPs suspension, as shown in Fig. 1.3(b). The TEM images of the colloidal Au/antibody homo-oligomeric structures before and after the addition of mono-specific linkers are shown in Fig. 1.3(c) [1].

Another experiment about understanding the factors that control the optical properties of DNA-linked gold NPs aggregates containing oligonucleotide linkers of varying duplex spacer length (24, 48, 72 base pairs) is described. In this system directed by James J. Storhoff et al., ~15 nm diameter Au NPs modified with alkanethiol-12 base oligomers are hybridized to the oligonucleotide linkers described above [2]. The overall idea of this experiment is illustrated

in Fig. 1.4(a) [2]. Aggregated at room temperature, the various macroscopic NPs assemblies have surface plasmon frequency changes that are inversely dependent on the duplex spacer length of oligonucleotide linkers. Originally, the DNA-modified Au NPs solutions are dark red in color with a surface plasmon frequency band centered at 524 nm. After adding oligonucleotide linker of varying duplex spacer to the solution of DNA-modified Au NPs A and B, the surface plasmon frequency band gradually red-shifted from 524 nm as aggregate growth occurred through DNA hybridization, and eventually macroscopic aggregates are visible to naked eye in suspension. For this set of experiment, the macroscopic DNA-linked aggregates (1-3) exhibited final surface plasmon band shifts at $\lambda_{\text{max}} = 581 \text{ nm}$ (1), 550 nm (2), and 540 nm (3), where the magnitude of the plasmon frequency change from 524 nm was inversely dependent on duplex spacer length of oligonucleotide linkers. The TEM images of DNA-linked Au NPs aggregates 1-3 are shown in Fig. 1.4(b) [2].

After reviewing on some significant experiments about the combination of tailored biomolecules---proteins and oligonucleotides and metal NPs---Au and Ag NPs, we shall start to review some experiments about semiconductor NPs. Among many semiconductor NPs, CdSe NPs have shown their unique attraction due to their spectacular size-dependent properties. As physical size of CdSe NPs approaches molecular dimension (less than 10 nm), the quantization effect becomes dominant, and many corresponding physical and chemical properties of bulk CdSe material become quite different and size-dependent [4]. For example, the band gap increase as the size of CdSe NPs decrease, resulting in the blue-shift of absorbance and luminescence spectra. Furthermore, the redox potential, fluorescence Stokes shifts, and phase transition, like melting point, also vary with the size of CdSe NPs. Among these dramatic properties, the size-dependent optical properties are the most attractive ones, because they enable CdSe NPs to serve as fluorescent labels on organic molecules for biological application, like monitoring of several reaction processes at the same time. However, due to incomplete surface passivation resulting in dangling bonds at the surface of

CdSe NPs, they have low fluorescent quantum yield. But if a “core” nanocrystal is passivated in a “shell” of wider bandgap semiconductor material, the resulting core/shell CdSe NPs becomes highly luminescent. The core/shell structure has several advantages, including resistance to photodegradation, improved brightness, and narrow-emission spectra. To target fluorescent nanocrystals to biological molecules, core/shell CdSe NPs must be derivatized. One of the most representative experiments about using fluorescent CdSe NPs as biological labels for convenient observation is shown below. Jason R. et al. covalently linked fluorescent CdSe NPs to DNA binding proteins, EcoRI, to probe specific sequences on single stretched DNA molecules [3]. For single DNA molecules that are stretched and immobilized on a solid surface, CdSe NPs bound at specific site can be directly visualized by multicolor fluorescent microscopy. Direct observation of site-specific probes on single DNA molecules opens new possibilities in optical gene mapping and in the fundamental study of DNA-protein interactions. The images of EcoRI conjugated NPs to single λ -DNA molecules are shown in Fig. 1.5.



1.3 MOTIVATIONS

In this work, we want to achieve several goals as below: ***First, in size regime, to fill the gap (10~100 nm) between top-down and bottom-up processes by using inorganic NPs.*** As we have discussed previously, the top-down processes, such as the photolithography method in conventional semiconductor fabrication process, currently reach a limit of 90 nm. Any miniaturization beyond this size will face more and more difficulties, including apparent quantization effects, dominant parasitic components of wires, and being very susceptible to electro static discharge (ESD). In opposite direction, the bottom-up processes, such as conventional chemical synthesis process, also have a limit at 2~5 nm. In this work, we use Au NPs (15 nm in diameter) and CdSe NPs (5~10 nm in diameter) to make a connection to both functional small organic compounds and larger microelectronics components, like the Al

electrodes on silicon chip. *Second, to construct functional nanodevice composed of inorganic NPs directly on the surface of silicon chip, where a CMOS sensing circuit is designed to linearly amplify the signal.* As we discussed above, current technology of photolithography method in semiconductor fabrication process has a limit of 90 nm in two-dimensional design. However, there is still plenty of room at the top of silicon substrate in three-dimensional design. In this work, the photo-sensing nanodevice is constructed directly on the surface of silicon chip to make a perfect combination of nanoclusters and microelectronics, without damage of the circuits in silicon chip. *Third, to investigate and utilize the molecular interaction forces to assemble NPs on silicon oxide substrate.* The NPs have the same crystal structure as the bulk material but consist of only a few hundred or thousand atoms. Therefore, interaction forces between molecules, such as hydrogen bonds, coulombic force, and Van der Waal Force, are also effective for NPs and play an important role in the assembly process. For example, the negative charges coming from citrate acids on Au NPs surface will prevent the particles from random aggregation and promote the assembly process of Au NPs with other positive-charged NPs.

1.4 THESIS ORGANIZATION

In chapter 1, we are given a background introduction, including the basic concepts, definition and current trend of nanotechnology development in the world. Then, we have some reviews on the most representative experiments about application on Au NPs and CdSe NPs. At last, we will have the motivations of this work and thesis organization.

In chapter 2, we will focus on the mechanism of photoconductivity of CdSe NPs and the electron transportation between NPs. We will also introduce and explain some phenomena, like quantum confinement of CdSe/ZnS NPs, in physical chemistry way.

In chapter 3, we will develop the two systems---DNA hybridization system and Coulombic force system, which are able to control NPs in nanostructure formation on silicon

oxide substrate. In this chapter, all the necessary synthesis and modification process will be illustrated clearly, and all photographs and microscope images of the experimental results will be shown with no exception.

In chapter 4, Hspice simulation and the measurement results of CMOS sensing circuits are shown. Then, the SEM images of the construction of photo-sensing nanodevice on silicon chip are shown. At last, the final measurement environment setup and results of nanodevice on silicon chip are both shown.

In chapter 5, we will have a brief conclusion of this work and the future work will also be mentioned.



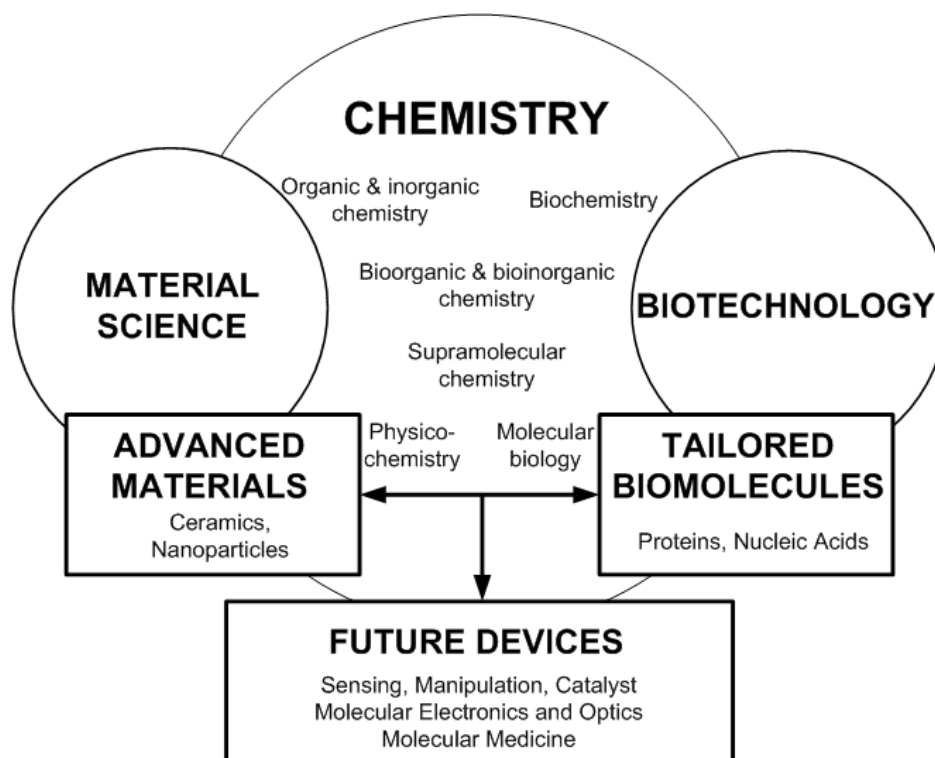


Fig. 1.1 Chemistry is the central science for further applications such as material science and biotechnology. The combination of advanced materials and tailored biomolecules will produce the future nanodevices [1].

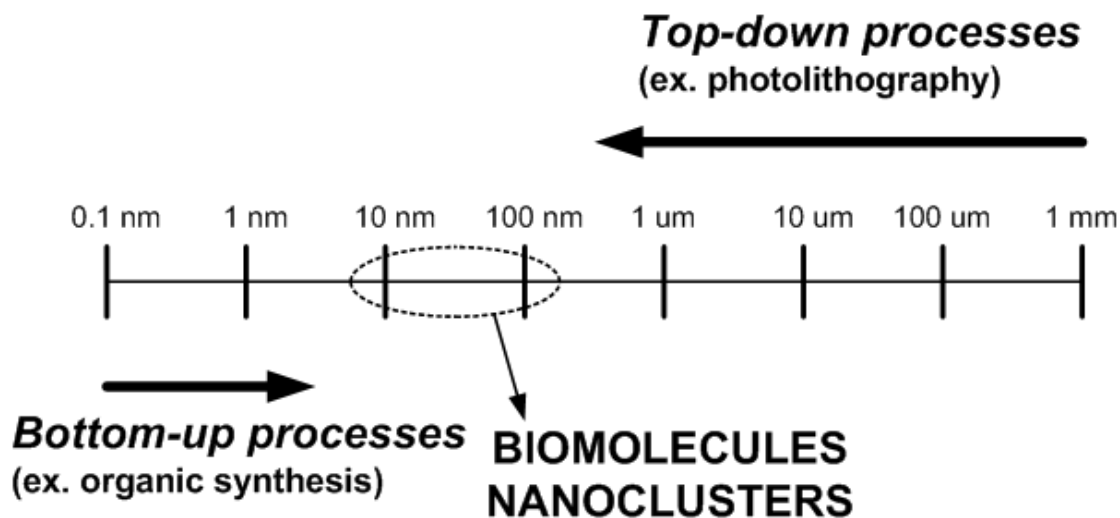


Fig. 1.2 The top-down processes will have their limit below 100 nm, and the bottom-up processes will also have a limit at 2~5 nm. The gap will be filled by nanoclusters and biomolecules [1].

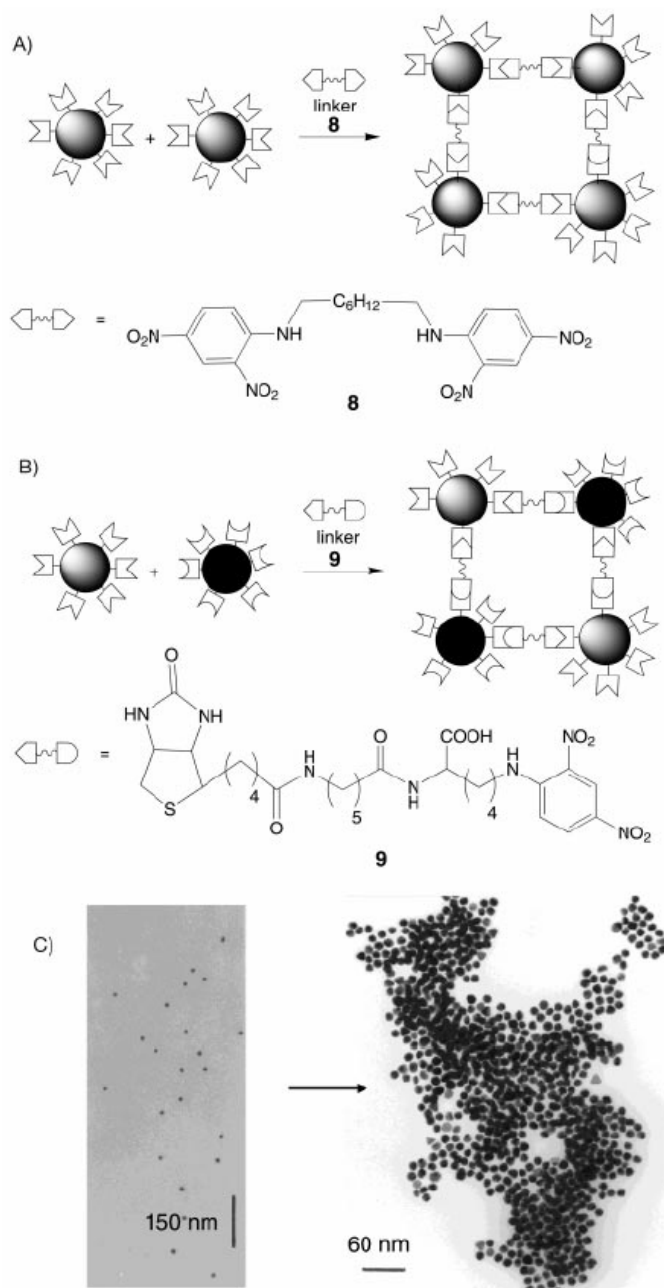
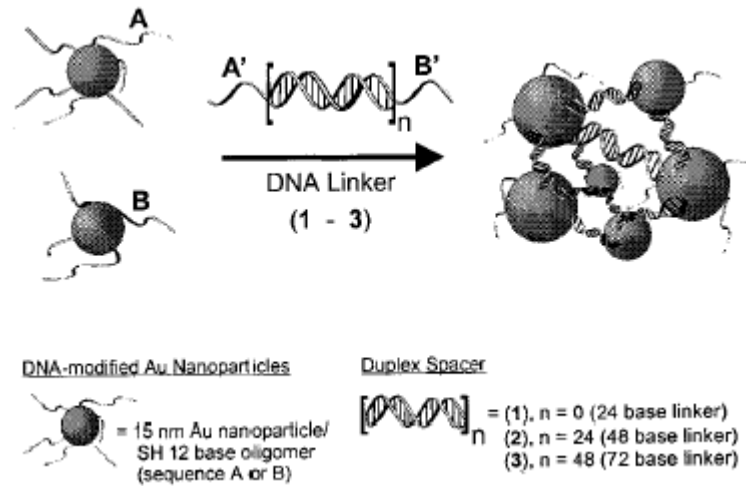
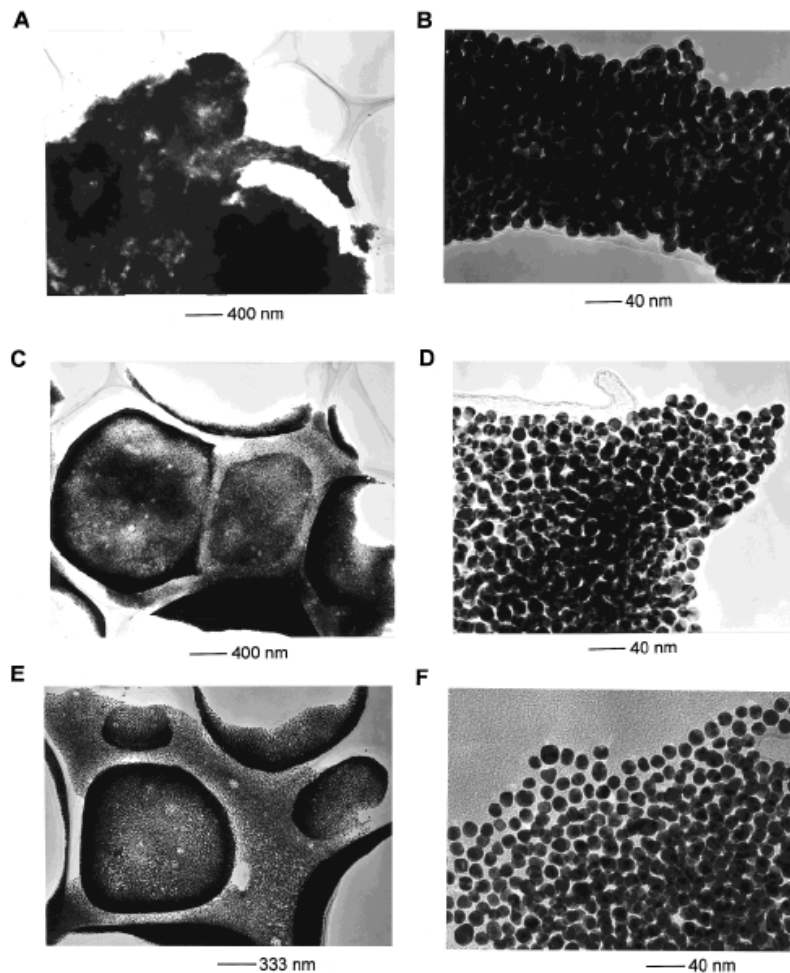


Fig. 1.3 The overall idea of Ag-Au NPs networks formation by taking advantage of the interaction between antibodies and low molecular weight hapten groups. Bivalent linkers with terminal hapten groups, either mono-specific 8 or bi-specific 9, allow the directed assembly of homo-oligomeric (a) or hetero-oligomeric (b) structure, respectively. The TEM images (c) were obtained from colloidal Au/antibody aggregates before and after the addition of linker 8 [1].



(a)



(b)

Fig. 1.4 (a) ~15 nm diameter Au NPs modified with alkanethiol-12 base oligomers are hybridized to the oligonucleotide linkers of varying duplex spacer length (24, 48, 72 base pairs). (b) The TEM images of DNA-linked Au NPs aggregates 1-3 are shown. (A) A portion of a 24 base linked aggregate 1. (B) A higher magnification image of the area in part A. (C) A 48 base linked aggregate 2. (D) A higher magnification image of the area in part C. (E) A 72 base linked aggregate 3. (F) A higher magnification image of the area in part C.

(E) A 72 base linked aggregate **3**. (F) A higher magnification image of the area in part E. Scale bars for each image are shown at the bottom of the micrograph [2].

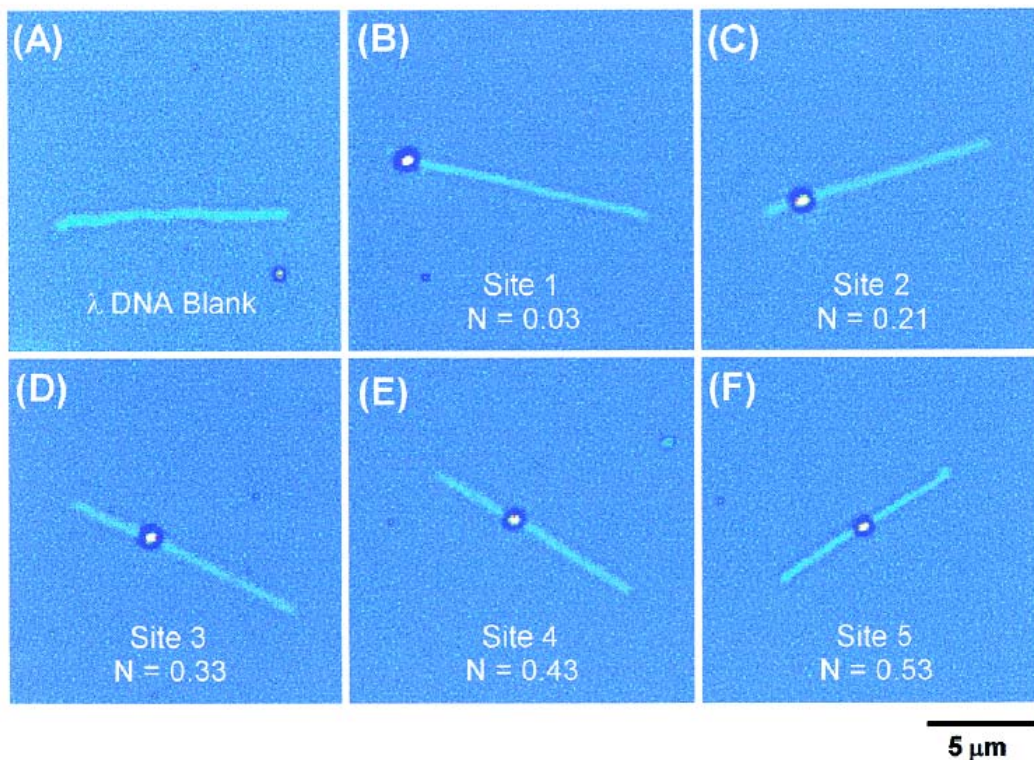


Fig. 1.5. Specific binding of EcoRI conjugated NPs to single λ -DNA molecules. Image (A) is a stretched DNA without binding particles. Images (B) to (F) show single NPs bound to sites 1-5. N denotes the normalized experimental position for bound particles [3].