

# Design and Fabrication of a Photosensing Nanodevice Structure With CdSe and Au Nanoparticles on a Silicon Chip

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**Abstract**—A newly developed four-layered photosensing nanodevice was fabricated by integrating nanoparticles (NPs) on a silicon substrate. Through ionic interaction, negatively charged Au NPs ( $\sim 15$  nm) were assembled in alternate layers with positively charged CdSe NPs ( $\sim 5$  nm) on the silicon oxide surface between the two Al electrodes. The silicon oxide surface after each step of the fabrication process was observed and evaluated by images obtained from the scanning electron microscope. By applying voltage biases across the electrodes, the currents were measured in the dark and under illumination using a 375-nm laser. It was found that a constant photocurrent increment can be obtained for different voltage biases, and the nanodevice structure with a longer length had less conductivity but a larger increment of photocurrent after illumination. In addition, the efficiency rate of photocurrent generation is much higher in comparison to that obtained from CdSe thin film. The fabrication process integrated a newly developed model of a diode-resistor array of semiconductor-metal junctions between CdSe and Au NPs (nano-Schottky-diode structures), which can successfully explain the measured results. While nanotechnology has unprecedented advantages over the traditional silicon electronics, its technology presents physical challenges. However, the success of the fabrication of the multilayered photosensing nanodevice directly on the silicon chip paves the way for further applications and research.

**Index Terms**—Nanotechnology, photocurrent, photodetectors, Schottky diodes.

## I. INTRODUCTION

RECENT research on the development of various new nanodevices/nanostructures with unique optical and electrical properties has increased significantly. Among these nanodevices/nanostructures, semiconductor nanoparticles (NPs) exhibited spectacular size-dependent characteristics when the particle size is less than 10 nm [1]–[3]. These interesting properties are caused by the discrete energy level spacing at the edges of conduction and valance bands when the size of the nanocrystal approaches molecular scale, producing the quantum-size effect. As the particle size becomes smaller, the highest occupied molecular orbit–lowest unoccupied molecular orbit (HOMO–LUMO) gap becomes larger, resulting in the blue shift of UV-visible absorption spectrums [4]. For metal NPs, the Fermi level lies at

the center of one continuous band. As a result, across the entire size range, the optical and electrical behaviors of metal NPs are described using classical equations for corresponding bulk material rather than quantum mechanical concepts [5].

Most recently, Au–CdSe–Au nanowires of 350-nm diameter were fabricated using a template growth method [6]. The anodic aluminum oxide template was used as molds, and CdSe and Au segments were deposited alternately to form the nanowires, where the CdSe was sandwiched between Au segments. This composite nanowire was found to exhibit significant photoconductive behavior with a 15-fold increase in conductivity under the illumination of visible light. The Au–CdSe–Au nanowires can function as sensitive photo sensors, which can potentially be massively multiplexed in devices of small size. However, with conventional silicon chips, the fabrication process and the electrofluidic alignment method of nanowires as described were not feasible. Consequently, since the potential application of this device on silicon chips is severely limited, a new type of nanomaterial and/or a new process for the fabrication of nanodevices on silicon chips arises.

The process of assembling different NPs onto the silicon chips is developed and investigated in this paper. In contrast to other nanostructures, NPs with uniformly distributed size and spherical shape were found to be better for the assembly process and the formation of a compact nanostructure. Experimentation has also shown that by using NPs in solution, the process of “dipping and washing” is the simplest and most effective process for the fabrication of nanodevices on the silicon chips. This process was adapted successfully to assemble NPs directly on the chip surface.

To control the assembly of NPs into a well-defined nanostructure, two types of forces, hydrogen bonding and ionic interaction, are commonly present [7]–[9]. Generally, with work involving self-assembly processes, nucleotides with various lengths were employed to take advantage of their self-recognition and self-assembly abilities [10]. However, nucleotides, particularly in the basic condition, are susceptible to cleavage, which presumably results from many steps of chemical reactions and consequently damages nucleotides and/or NPs. These chemical modifications are performed either on the 5'- or 3'-end of the oligo-nucleotide or NPs to create an active center so that the nucleophilic and the electrophilic reactions can take place. Furthermore, to integrate NPs on the silicon chip through DNA self-assembly, the same chemical modifications for primer conjugation are also needed for the chip. Using many chemical modifications, serious damage of the metal structures on the chip surface may happen. Using the

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ionic interaction system, on the other hand, the chemical modification process can be reduced to a minimum. Methods have been developed to efficiently modify the substrate and NPs by attaching highly concentrated ionic groups, such as carboxylate and amino groups, to them. When NPs are assembled on the substrate by ionic interaction, the sum of the multiple interactions forced on one NP can be comparable to a covalent bond. Consequently, the NPs can be firmly assembled on the chip by using of the “dipping and washing” process repeatedly. In this paper, the ionic interaction system was employed to integrate CdSe and Au NPs onto a silicon chip. The photosensing properties of this unique nanodevice were measured and discussed.

## II. EXPERIMENTAL SECTION

### A. Synthesis of $\sim 15$ -nm Diameter Au NPs by Citrate Reduction Method

Au NPs with  $\sim 15$  nm in diameter were prepared by citrate reduction of  $\text{HAuCl}_4$ , as described in literature [10]. The pale yellow  $\text{HAuCl}_4$  solution (1 mM, 500 mL) was prepared and refluxed, while being stirred, for 20 min. A solution of citric acid (38.8 mM, 50 mL) was then quickly injected into the flask. The color of the solution changed from pale yellow to deep red indicating the formation of Au NPs. After refluxing for an additional 20 min, the solution was cooled at room temperature for another 30 min before being filtered through a  $0.45\text{-}\mu\text{m}$  Nylon filter. Physically, it is the complete surface coverage of citric acid molecules that stops the Au nanocrystals from growing. Therefore, with the assumption of 100% surface coverage, each Au NP with  $\sim 15$ -nm diameter is estimated to have about 900 carboxylate ( $-\text{COO}^-$ ) groups on the particle surface, each group carrying one negative charge.

### B. Synthesis and Modification of $\sim 5$ -nm Diameter CdSe NPs With Tyramine

The synthesis process of the fluorescent n-hexadecylamine (HDA)-coated CdSe NPs with  $\sim 5$  nm in diameter was reported in literature [11] and was employed in this paper. The 80-mg HDA-coated CdSe NP powder and 600-mg tyramine powder were dissolved in 5 and 10 ml of dried methanol, respectively. Tyramine was completely dissolved in methanol, while the HDA-coated CdSe NP's powder formed a suspension in methanol after ultrasonication. After mixing the two solutions, the catalyst, 1 mL of 25 wt% tetramethylammonium hydroxide/methanol, was added for the displacement of the HDA molecules. The mixture was refluxed at  $70^\circ\text{C}$  for 12 h in a dark environment. The resulting solution was kept at room temperature for 30 min. To prevent the aggregation of NPs, 30 mL of chloroform and 10 mL of PBS buffer solution (5 mM  $\text{Na}_2\text{HPO}_4$ , pH 7.0) were added to the methanolic solution. The mixture was shaken vigorously and was left at room temperature for 10 min to allow phase separation. The upper layer, containing tyramine-modified CdSe NPs and some suspended particles (removed by low-speed centrifugation), was collected and extracted with chloroform several times to remove the potential contaminants, such as the unreacted tyramine. The resulting solution consisting of tyramine-modified CdSe NPs was vacuumed to dryness and redissolved in deionized water for further study [12]. The accurate surface coverage of tyramine on a CdSe NP

is difficult to determine; however, the maximum coverage is estimated to be about 200 tyramine molecules per CdSe NP [12]. Each tyramine molecule carries one positive charge.

### C. Design and Fabrication of Electrode Structure on Silicon Chip

The silicon chip used in this paper was fabricated in  $0.35\text{-}\mu\text{m}$  2P4M CMOS technology. The electrode structure was formed by opening a passivation window ( $86\ \mu\text{m}^2$ ) over a pair of closely separated ( $5\text{--}15\ \mu\text{m}$ ) Al metal lines. The two metal lines were connected to two bonding pads on the chip, respectively. The conceptual cross-sectional figure of the electrodes structure is shown in Fig. 1(a). The spacing of the gap defines the length of the electrodes, while the width is defined by the diameter of the metal lines. The surface of the silicon oxide region between the two metal lines provides the application area for nanodevice fabrication. The two metal lines, on the other hand, serve as two electrodes that make close attachment to the nanodevice. The electrodes of two different sizes,  $30/15\ \mu\text{m}$  and  $30/5\ \mu\text{m}$  (width/length), were both employed in this paper.

### D. Fabrication of Four-Layered Photosensing Nanodevice on Silicon Oxide Surface of Silicon Chip

The designated silicon chip was first cleaned by  $\text{N}_2$  flow to remove nonspecific particles attached on the surface. The chip was then immersed in a 10% N-[3-(trimethoxysilyl)propyl] ethylene diamine (TMSPED)/methanol solution for 20 min and further washed by methanol to remove excess TMSPED [13]. The concentration of the TMSPED/methanol solution and the time for immersing the chip determine how much TMSPED was anchored and, thus, the density of Au NPs, which was estimated to be about 700 particles per  $\mu\text{m}^2$  in the first layer. However, the area density is gradually saturated when TMSPED concentration is above 5%. The resultant chip was then dipped in 30-mM HCl for a few seconds and washed several times with deionized water to protonate the amino groups of tyramine. Note that to prevent the oxidation of Al metal lines, the concentration of HCl and the dipping time must be carefully controlled. Finally, the TMSPED-treated chip was dried and kept under vacuum for further application. The conceptual cross-sectional figure of the silicon oxide surface after this step is shown in Fig. 1(b).

For the assembly of Au NPs on the silicon oxide surface, the TMSPED-treated silicon chip was first immersed into the solution of Au NPs for 12 h. After the immersion, the silicon chip was cleaned by deionized water several times to remove free Au NPs and then dried under vacuum. The conceptual cross-sectional figure for the assembly of Au NPs is shown in Fig. 1(c). The silicon chip was then immersed in the tyramine-modified CdSe NPs solution for a further 12 h to allow the assembly of CdSe NPs onto the formerly immobilized Au NPs by ionic interaction. The cross section of the resultant chip is illustrated in Fig. 1(d). By repeating the above process, a four-layered photosensing nanodevice was fabricated. The nanodevice structure is illustrated in Fig. 1(e).

### E. Measurement of Photosensing Nanodevice on Silicon Chip

After fabrication, the resultant chip was assembled firmly on a stage, and wires were attached to the bonding pads to allow

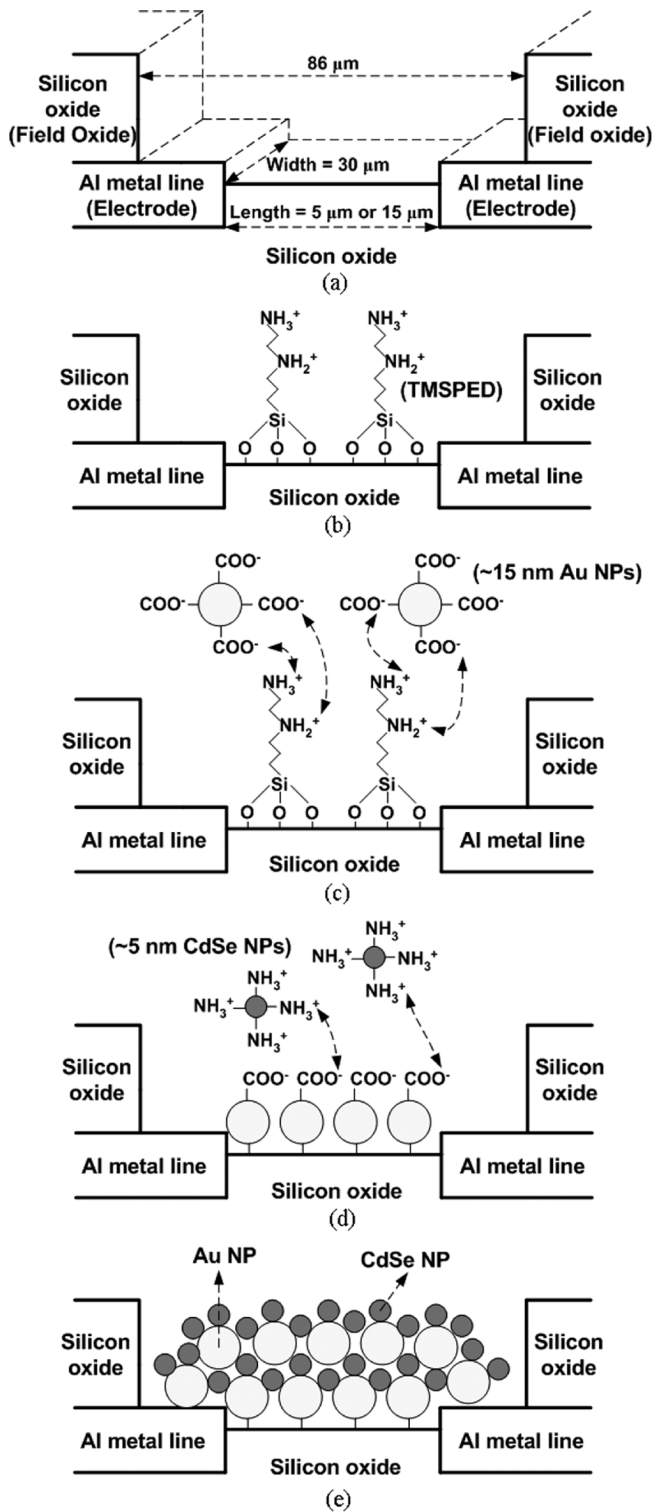


Fig. 1. Overall fabrication process of four-layered photosensing nanodevice composed of CdSe and Au NPs on conventional silicon chip. (a) Cross-sectional figure of Al electrodes structure used, where passivation window ( $86 \mu\text{m}^2$ ) was opened over two closely separated ( $5$  or  $15 \mu\text{m}$ ) Al metal lines. (b) Silicon oxide surface was then modified with TMSPED molecules. (c) Chemically prepared Au NPs ( $\sim 15 \text{ nm}$  in diameter) were assembled on silicon oxide surface by ionic interaction. (d) Tyramine-modified CdSe NPs ( $\sim 5 \text{ nm}$  in diameter) were assembled on formerly immobilized Au NPs by ionic interaction. (e) Formation of the four-layered nanostructure after another identical assembly process. Note that counter ions are ignored in these figures.

the measurement of photocurrent. By applying voltage biases (from  $0$  to  $0.6 \text{ mV}$ ) across the electrodes, the currents generated

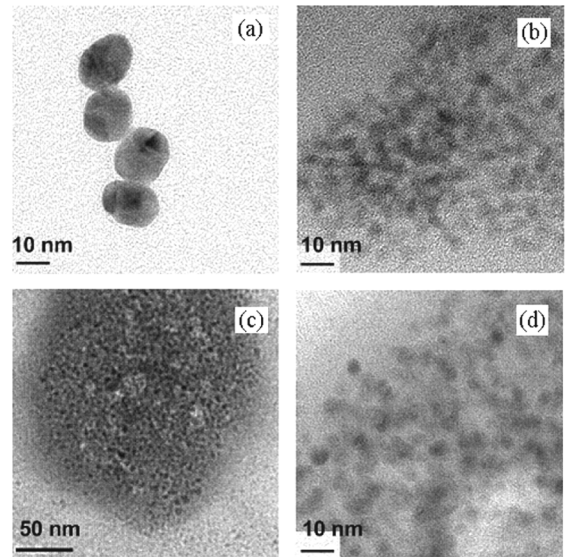


Fig. 2. TEM images of Au, CdSe NPs, and granule of self-assembled two NPs. (a) Chemically prepared Au NPs ( $\sim 15 \text{ nm}$  in diameter). (b) Tyramine-modified CdSe NPs ( $\sim 5 \text{ nm}$  in diameter). (c) Aggregates of Au and CdSe NPs ( $\sim 200 \text{ nm}$  in diameter). (d) Large magnification of edge part of (c).

were measured both in the dark and under the illumination of a  $375\text{-nm}$  laser with a constant power of  $0.5 \text{ mW}$ .

### III. EXPERIMENTAL RESULTS AND DISCUSSION

#### A. Design and Fabrication of Photosensing Nanodevice

The fabrication of the photosensing nanodevice was designed using the “dipping and washing” process, as illustrated in Fig. 1. In general, the chip was first modified by either 3-aminopropyltriethoxysilane (APTES) or N-[3-(trimethoxysilyl)propyl]ethylene diamine (TMSPED) to provide a source of positively charged amino groups. Through ionic interaction, chemically prepared Au NPs ( $\sim 15 \text{ nm}$ ) and tyramine-modified CdSe NPs ( $\sim 5 \text{ nm}$ ) were assembled a layer at a time, alternately, between the two Al electrodes.

No chemical reaction was involved as the whole assembly process of NPs depended only on the physical attractions between the NPs and substrate. In the proposed four-layered nanodevice structure as shown in Fig. 1(e), the Au NPs serve as bridges between the CdSe NPs and the electrodes, enhancing the overall conductivity of the photosensing nanodevice. In addition, the semiconductor-metal junctions between the CdSe and Au NPs contribute significantly to the overall photosensing ability.

#### B. Images of Au and Tyramine-Modified CdSe NPs

After the synthesis of Au NPs and tyramine-modified CdSe NPs, the particle size was measured using images obtained from the transmission electron microscope (TEM). The TEM image of the Au NPs with  $\sim 15 \text{ nm}$  in diameter is shown in Fig. 2(a). The TEM image in Fig. 2(b) showed that the CdSe NPs are  $\sim 5 \text{ nm}$  in diameter. Fig. 2(c) and (d) shows the TEM images of a mixture of  $100 \mu\text{L}$  of the Au NPs solution and  $100 \mu\text{L}$  of the tyramine-modified CdSe NPs solution, which had been standing for  $6 \text{ h}$  at room temperature. As can be seen in Fig. 2(c) and (d), the Au and CdSe NPs interact with each other through

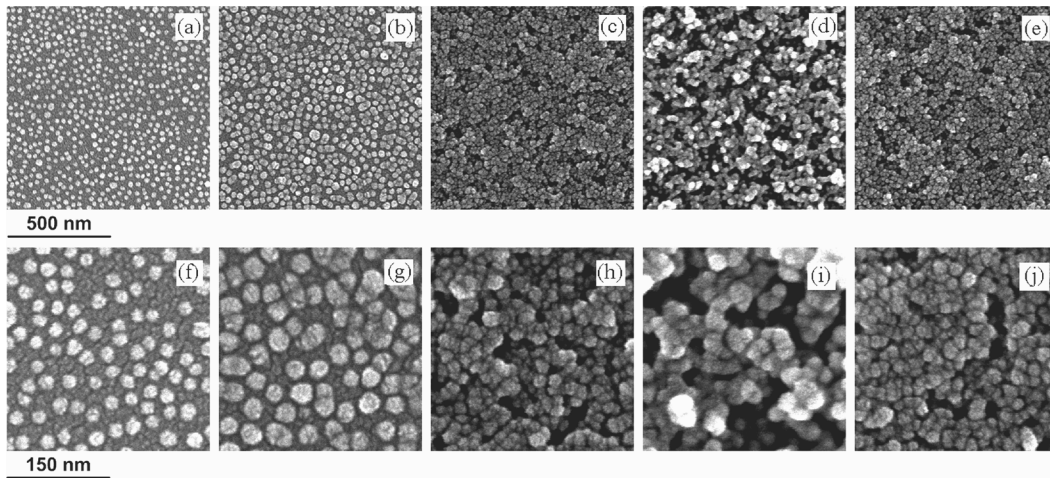


Fig. 3. SEM images of (a)-(e) 50-k magnification and (f)-(j) 150-k magnification. (a), (f) Au NPs/SiO<sub>2</sub> (Au NPs assembled on SiO<sub>2</sub> substrate). (b), (g) CdSe NPs/Au NPs/SiO<sub>2</sub>. (c), (h) Au NPs/CdSe NPs/Au NPs/SiO<sub>2</sub>. (d), (i) CdSe NPs/Au NPs/CdSe NPs/Au NPs/SiO<sub>2</sub>. (e), (j) Au NPs/CdSe NPs/Au NPs/CdSe NPs/Au NPs/SiO<sub>2</sub>. Note that for better resolution, 3-nm thickness of Pt was plated on each sample prior to SEM.

ionic interaction, resulting in the formation of granules with ~ 200 nm in diameter. After three days, obvious precipitation was observed at the bottom of the tube, indicating the aggregation of CdSe and Au NPs.

*C. Assembly of Au NPs and Tyramine-Modified CdSe NPs on Silicon Chip*

The overall fabrication process of the four-layered photosensing nanodevice was observed and evaluated by scanning electron microscopy (SEM) images at each stage of the procedure. The initial stage involved assembling the negatively charged (–COO<sup>–</sup>) Au NPs on the positively charged (–NH<sub>3</sub><sup>+</sup>) silicon oxide surface by ionic interaction to form the first layer (Au NPs/SiO<sub>2</sub>), as shown in Fig. 3(a) and (f). Due to the ionic repulsive forces between the Au NPs, the Au NPs were nearly uniformly labeled on the surface without being in contact with each other. The distance between Au NPs was within 5 to 20 nm in range. The second stage involved the alignment of the positively charged (–NH<sub>3</sub><sup>+</sup>) CdSe NPs onto the previously immobilized Au NPs to form the double-layered structure (CdSe NPs/Au NPs/SiO<sub>2</sub>), as shown in Fig. 3(b) and (g). The overlay of CdSe NPs on the Au NPs causes the formation of larger granules with 30 to 40 nm in diameter. This increase in size causes the distance between the granules to become smaller than that as shown in Fig. 3(a) and (f). In the third stage, ionic interaction causes the Au NPs to be assembled on the former nanostructure to form a closely packed layer of Au NPs on the top, resulting in a three-layered structure (Au NPs/CdSe NPs/Au NPs/SiO<sub>2</sub>), as shown in Fig. 3(c) and (h). Due to the accumulated density of Au NPs, the shining golden color can be easily observed by the naked eye. This feature provided a convenient way to examine the effectiveness of the assembly process. The photosensing nanodevice with a four-layered structure (CdSe NPs/Au NPs/CdSe NPs/Au NPs/SiO<sub>2</sub>) was fabricated as described above and shown in Fig. 3(d) and (i). Theoretically, the ionic assembly using this dip-and-wash process can be repeated several times. Hence a five-layered structure (Au NPs/CdSe NPs/Au NPs/CdSe NPs/Au NPs/SiO<sub>2</sub>) can be easily obtained after another closely packed Au NPs

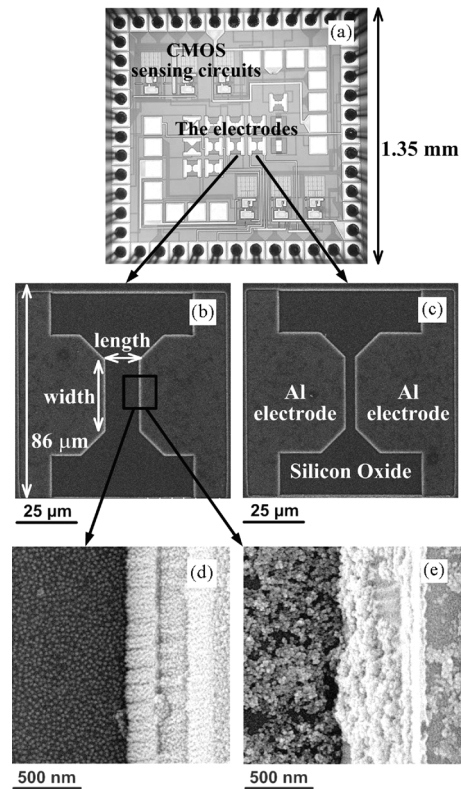


Fig. 4. Images of electrodes at different stages. (a) Optical microscope image of silicon chip. (b), (c) SEM images of two types of electrodes of size 30/15 μm and 30/5 μm (width/length). (d), (e) Large magnification of edge part of electrodes after fabrication of layer of Au NPs (Au NPs/SiO<sub>2</sub>) and four-layered structure (CdSe NPs/Au NPs/CdSe NPs/Au NPs/SiO<sub>2</sub>).

layer was formed on top of the four existing layers, and the structure is shown in Fig. 3(e) and (j).

*D. Measurement of Photosensing Nanodevice on Silicon Chip*

The optical microscope image of the silicon chip before the fabrication of the nanodevice is shown in Fig. 4(a), where electrodes of various shapes and sizes were fabricated at the central part. The SEM images of the two sets of electrodes, 30/15 μm

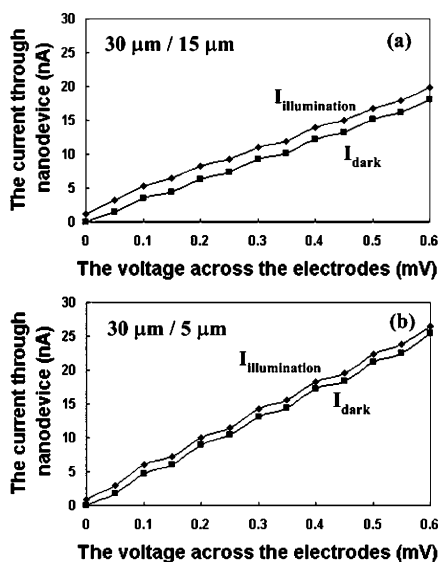


Fig. 5. Measurement results of nanodevice with and without illumination. Two sets of electrodes, (a)  $30/15 \mu\text{m}$  and (b)  $30/5 \mu\text{m}$ , were investigated.  $I_{\text{dark}}$  means current measured in dark, while  $I_{\text{illumination}}$  represents current measured under illumination of 375-nm laser. (Average  $R = 1/\text{slope of } I\text{-}V \text{ curves}$ ).

and  $30/5 \mu\text{m}$  (width/length), which were employed in this paper, are shown in Fig. 4(b) and (c). The images recorded by the edge of the electrodes after the fabrication of the single-layered structure of Au NPs/ $\text{SiO}_2$  and the four-layered structure CdSe NPs/Au NPs/CdSe NPs/Au NPs/ $\text{SiO}_2$  are shown in Fig. 4(d) and (e), respectively. It is interesting to note that, in addition to the silicon oxide surface, the surface of Al electrodes was also labeled with NPs. This phenomenon may be caused by the presence of the  $-\text{OH}$  groups on the surface of the electrodes, which can be modified by TMSPED molecules, making them suitable sites for NP assembly. The presence of NPs on the Al electrodes enhances continuity at the interface between the NP's packed silicon oxide surface and the electrodes. The reflective UV-visible spectrum of the four-layered photosensing nanodevice structure was examined with a clean  $\text{SiO}_2$  substrate as blank, and the spectrum was found to exhibit a gradual increment of absorbance from 600 to 350 nm. Therefore, a laser with a wavelength of 375 nm was employed for the photoactivation investigation.

For the structure with only a layer of Au NPs on the silicon oxide surface (Au NPs/ $\text{SiO}_2$ ), the  $I\text{-}V$  characteristics were virtually identical to those of the open electrodes. A current of less than 10 fA was observed throughout the applied voltages, with or without illumination. The relatively large distance [5–20 nm, Fig. 3(f)] between the Au NPs prohibited the electrons from tunneling between the NPs and electrodes. However, for the four-layered structure (CdSe NPs/Au NPs/CdSe NPs/Au NPs/ $\text{SiO}_2$ ), the nanodevice was resistive in the dark and produced a constant increment of photocurrent after illumination. The measurement results of the four-layered nanodevice are shown in Fig. 5.

There are several notable characteristics of the results, and a new model is developed to explain the measured characteristics. First, the increment of photocurrent throughout the applied voltage biases after illumination was found to be con-

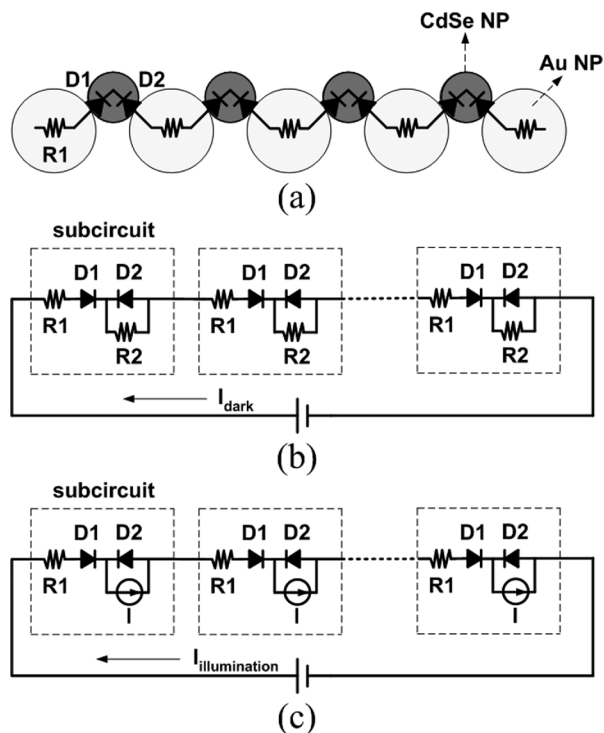


Fig. 6. (a) One-dimensional array of nano-Schottky-diodes and resistors, where  $D1$  represents forward-biased Schottky diode,  $D2$  is reverse-biased Schottky diode, and  $R1$  is resistance of Au NP. (b), (c) Models for nanodevice in dark and under illumination. For Hspice simulation, Fowler–Nordheim diode model was employed,  $V = 0.4 \text{ V}$ ,  $R1 = 1 \text{ M}\Omega$ ,  $R2 = 5 \text{ M}\Omega$ , and  $I = 5 \text{ pA}$ .

stant and specific to the electrode type 2 nA ( $30/15 \mu\text{m}$ ) and 1.2 nA ( $30/5 \mu\text{m}$ ). In the proposed nanodevice structure, there are many semiconductor–metal junctions formed at the interfaces between CdSe and Au NPs, as shown in Fig. 1(e). They are called the “nano-Schottky-diodes” because of the nanoscale and the semiconductor–metal contact. The small size and high surface-to-volume ratio of NPs causes a massive number of nano-Schottky-diode structures to be formed in a very small volume. Unlike the conventional bulk CdSe/Au Schottky contacts, there are many modifying molecules residing at the small contacting interfaces between CdSe and Au NPs, such as the tyramine molecules labeled on CdSe NPs and the carboxylate groups labeled on Au NPs. Although those molecules retain resonance structures, such as the carboxylate ions and phenol moiety of tyramines, the electrons of these structures can only delocalize locally among few resonant atoms. Therefore, the modifying molecules at the junction interface basically serve as a very thin insulator with a thickness less than 1 nm, a distance that still allows the effective tunneling of electrons. Since the Au NPs have low conductivity due to their small size, they can be treated as resistors. Thus, the proposed CdSe/Au nanodevice structure forms a three-dimensional array of nano-Schottky-diodes and resistors, as shown in Fig. 6(a). For simplicity of discussion, only one-dimensional array is considered here. When applying a voltage bias between the two electrodes, the two nano-Schottky-diodes associated with a CdSe NP become forward-biased and reverse-biased, alternately, along one direction [14]. Since the CdSe NPs have a diameter of  $\sim 5 \text{ nm}$ , the reverse-biased nano-Schottky-diode causes its CdSe NP to be fully depleted even

under zero bias. With uniform photoexcitation ( $h\nu > E_g$ ), electron hole pairs generated within the CdSe depletion region of reverse-biased Schottky junctions are separated by the electric field with electrons swept to the Au NP of the forward-biased Schottky diode and holes swept to the Au NP of the reverse-biased Schottky diode, producing the photocurrent. Since the CdSe NP is fully depleted even at zero bias, the generated photocurrent is constant for different bias voltages; hence, the conductivity does not increase under light illumination as shown in Fig. 5. This characteristic is different from that of bulk CdSe, where the conductivity increases after illumination.

When compared to the conventional CdSe thin film [15], the four-layered photosensing nanodevice has a much higher photosensing efficiency. In [15], the CdSe thin film of 200-nm thickness was deposited on a glass substrate by thermal evaporation technique. The electrodes with a 3-mm space were made to measure the photoresponse. The results show that a generated photocurrent of 1.25 nA was observed under a 10-V voltage bias and a 7600-lux white light illumination. Photosensing efficiency is defined as the amount of generated photocurrent per unit volume under illumination. Using this definition, it was found that the efficiency of the proposed nanodevice was measured to be at least 27 000 times greater than that of the CdSe thin film. This high efficiency is caused by the fully depleted CdSe NPs and the extremely high density of nano-Schottky-diodes. This confirms the superiority of the fabricated photosensing nanodevice with CdSe and Au NPs on its silicon chip.

In addition to the property of constant increment of photocurrent, the conductivity of the proposed nanodevice structure varies with the length of electrodes with fixed width. The conductivity is decreased with the increased length, but the generated photocurrent under illumination is larger. As shown in the measurement results in Fig. 5, for electrodes with length of 15  $\mu\text{m}$ , the average resistance  $R$  was 33.1  $k\Omega$  and the average photocurrent  $I_{\text{illumination}} - I_{\text{dark}}$  is 2 nA. For electrodes with a length of 5  $\mu\text{m}$ , the average resistance  $R$  was 24.1  $k\Omega$  and the average photocurrent  $I_{\text{illumination}} - I_{\text{dark}}$  is 1.2 nA.

From the conduction mechanism of the array of nano-Schottky-diodes and resistors described above, a new model can be proposed to explain this characteristic. As shown in Fig. 6(b), in the dark, a large resistor  $R_2 = 5 \text{ M}\Omega$  is connected in parallel with the reverse-biased Schottky diode  $D_2$ , representing the small reverse-biased diode conductance, and the resistance of Au NPs is  $R_1 = 1 \text{ M}\Omega$ . Under steady illumination, the large resistor  $R_2$  is replaced by a very small current source  $I = 5 \text{ pA}$ , as shown in Fig. 6(c), representing the small photocurrent generated by a reverse-biased Schottky diode. In practice, there are thousands of conduction paths in parallel between the electrodes. Each path has a photocurrent in the picoampere scale (like 5 pA, in this paper). If they are all taken into summation, the resultant photocurrent is in the nanoampere scale which is equivalent to the photocurrent measured in the experiment. The circuits in Fig. 6(b) and (c) were further simulated by HSPICE with a voltage bias of 0.4 V. To simulate the nanodevice structure with long (short) length, 45 (15) subcircuits were connected in series. From the simulation results of Fig. 6(b) and (c),  $I_{\text{illumination}} - I_{\text{dark}} = 3.3 \text{ pA}$  for the longer chain (45 subcircuits), and 1.4 pA for the shorter

chain (15 subcircuits) were obtained. This confirms the measured characteristics that the nanodevice structure with a longer length has less conductivity but larger generated photocurrent under illumination. Physically, the larger photocurrent in the longer nanodevice structure is caused by the larger number of reverse-biased Schottky diodes. Each reversed Schottky diode has a forward photovoltaic voltage after illumination to effectively increase the overall bias voltage of the array and thus the photocurrent.

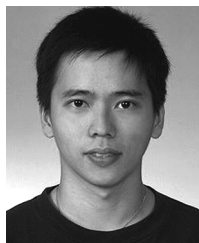
#### IV. CONCLUSION

The proposed four-layered photosensing nanodevice was fabricated by integrating CdSe and Au NPs on the silicon chip. Through ionic interaction, negatively charged Au NPs and positively charged CdSe NPs were assembled layer by layer, alternately, on the TMSPED-treated silicon oxide surface between the two Al electrodes. The success of the fabrication process was verified by SEM images and the photosensing properties of the nanodevice were measured and found to be highly favorable. Results showed that a constant photocurrent increment can be obtained for different applied voltage biases and the nanodevice structure with a longer length had less conductivity but a larger increment of photocurrent. The newly fabricated photosensing nanodevice presented here has a much greater photocurrent generation efficiency than that of conventional CdSe thin film. These  $I$ - $V$  characteristics mainly resulted from the enormous number of nano-Schottky-diode structures at the interfacing points between CdSe and Au NPs, where the reverse-biased Schottky diode fully depleted its CdSe NP and thus provided a constant photocurrent. Based on this mechanism, a new model of diode-resistor array was proposed and has successfully explained the measured results. Further applications and improvement on the proposed nanodevice is ongoing.

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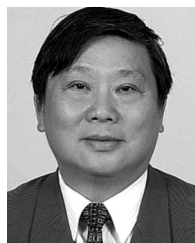
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