# CHAPTER 5

# CONCLUSIONS AND FUTURE WORKS

## 5.1 CONCLUTIONS

In this work, the function of ZnS layer was to improve the quantum yield of CdSe NPs. The proposed two kinds of multi-layered photo-sensing nanodevices were fabricated by integrating CdSe/ZnS and/or Au NPs on the silicon chip. The fabrication of the nanodevices was designed using the "dip-and-wash" procedure and the dip time was decreased to 20 min per layer which is sufficient to make saturated deposition. To control and assemble CdSe/ZnS and/or Au NPs into well-defined nanostructure, we utilized the ionic interaction between CdSe/ZnS and/or Au NPs or between NPs and silicon oxide substrate. First, the silicon chip was modified by N-[3-(trimethoxysilyl) propyl] ethylene diamine (TMSPED) to make the silicon oxide substrate provide amino groups ($-NH3^{+}$). Subsequently, Citrate-capped Au NPs (~15 nm)、MSA-capped and AET-capped CdSe/ZnS NPs (~5 nm) was self-assembled layer-by-layer, alternately, between the electrodes. The nanodevice structure after each layer was formed on the silicon oxide substrate was observed by SEM images. UV-visible and PL intensity spectra were used to verify the construction of each layer on quartz glass substrate. Finally, the electrical properties of the photo-sensing nanodevices were observed. The two electrodes sets, 30 μm / 15 μm and 30 μm / 5 μm (width / length) were employed for I-V measurement. The laser diodes of three kinds of wavelength, 375 nm, 400 nm and 435 nm, were used as light sources for nanodevice photo-excitation. For the nanodevice composed of Au and AET-CdSe/ZnS NPs, there was a constant increment of photocurrent after illumination throughout the applied voltage biases, which resembles the characteristics of a photodiode. Furthermore, the two-dimensional "nano-Schottky-diode" arrays model was proposed and used to explain the photo-sensing mechansims, and the high solar cell efficiency can be obtained

based on our ideal inference. For the nanodevice composed of positive-charged (AET-capped) and negative-charged (MSA-capped) CdSe/ZnS NPs, the photo-sensing properties resemble a common photoresistor, and have a higher photocurrent volume density than that of conventional CdSe thin film. In conclusion, there are some notable characteristics of the measurement results:

***Au / AET-CdSe/ZnS nano-schottky diode array***

（1）For the same Width and Excitation wavelength

In dark: Length ↑ -> Conductivity ↓

Under illumination: Length ↑ -> Conductivity ↓ , Photocurrent ↑

（2）For the same Width/Length and Excitation wavelength

In dark: Length ↑ -> Conductivity ↑

Under illumination: Length ↑ -> Conductivity ↑ , Photocurrent ↑ , PVD ↓

（3）For the same Width/Length and Layer

Excitation wavelength ↓ -> Constantly conductivity , Photocurrent ↑

（4）Maximum PVD = $8.21 * 10^{-22}$ ($A / nm^3$) , PVD Ratio = 1183

in 4-layered nanodevice, 30 μm / 15 μm electrodes

（5）Maximum photocurrent density per light power = 2.271 ($mA / cm^2 \cdot W$)

in 12-layered nanodevice, 30 μm / 15 μm electrodes

（6）Solar cell efficiency = 40% (ideal inference, not measurement data)

in 8-layered nanodevice, 30 μm / 26625,000 μm (23.1 $cm^2$) electrodes

***MSA-CdSe/ZnS / AET-CdSe/ZnS nanodevice***

（1）For the same Width and Excitation wavelength

In dark: Length ↑ -> Conductivity ↓

Under illumination: Length ↑ -> Conductivity ↑ , Photocurrent ↑

（2）For the same Width/Length and Excitation wavelength

In dark: Length ↑ -> Conductivity ↑

Under illumination: Length ↑ -> Conductivity ↑ , Photocurrent ↑ , PVD ↑

（3）For the same Width/Length and Layer

Excitation wavelength ↓ -> Conductivity ↑ , Photocurrent ↑

（4）Maximum PVD = 2.423 * $10^{-23}$ (A / $nm^3$) , PVD Ratio = 34

in 12-layered nanodevice, 30 μm / 15 μm electrodes

（5）Maximum photocurrent density per light power = 0.058 (mA / $cm^2$ • W)

in 12-layered nanodevice, 30 μm / 15 μm electrodes

## 5.2 FUTURE WORKS

***The future works of this project can be divided into seven parts:***

（1）In this project, we have developed the photo-sensing nanodevice composed of Au and AET-CdSe/ZnS NPs on silicon chip and discovered the ultra high power efficiency based on our inference. There is an important characteristic: Because the presence of the –OH groups on the surface of the electrodes, which can be modified by TMSPED molecules, making it suitable sites for NP assembly, consequently, resulting enhances continuity at the interface between the NP's packed silicon oxide surface and the Al electrodes. In theoretically, the NPs will be self-assembly covering the silicon chip. Although we cannot sure the edge between the Al electrodes and silicon oxide will be continuing self-assembly labeled with NPs firmly. Inevitably, other parts of ‘‘chip’’ contribute photocurrent as well as the electrodes under measurement. It further results in an inaccuracy when estimating the overall photocurrent generating from the electrodes. In the worse case, we must consider the whole chip area for calculation. The following works that we can do are to design and fabricate the electrodes of various sizes or large area size, and then to check whether the variation of

short-circuit current and open-circuit voltage its can confirm our ideal inference. Another work we can do is to modify the electrodes structure to construct the nanodevice on ITO/glass substrate. The above-mentioned is exploited to avoid unnecessary effect.

（2）In order to measure the nanodevice, using the aqueous insulation gel fix the nanodevice -modified silicon chip and then bonding wire from silicon chip on PCB board or blank package. Since, the quick-drying gel with organic solvent is not suitable and 125℃ heating process is extremely harmful to nanodevice during bonding. In the future work, we must improve the package method and set up the standard instrument for measurement. For example, using the probe replaces the traditional bonding wire and uses the solar energy simulator to measure the nanodevice. To stable nanodevice on air environment, we can use chemical methods to improve the QDs surface such as silanziation the QDs or self-assembly the polycation / polyanion on the top layer of the structure to restrain QDs oxidation.

（3）In this project, we used approximately 5 nm CdSe/ZnS NPs to construct the nanodevices. As we know that CdSe NPs have the size dependent optical and electrical properties, the band gap increases as the particle size decreases, shifting the absorption and luminescence spectra to the blue. The further research on CdSe/ZnS NPs is to synthesize the NPs of various sizes and then mix to each other. This goal is to achieve a board band absorption spectrum.

（4）Dye sensitization of mesoscopic $TiO_2$ has been widely used in solar cells—in which the sunlight creates bound electrons and holes—excitons—that travel as a unit and separate only after reaching some material boundary, resulting a board band absorption spectrum, and then raise the photo-to-charge carrier generation efficiency. In our future work, maybe we can employ charged-laser dyes (Cy2, Cy3, Cy5, FTIC, ...etc) to fill the gap between the assembled-NPs and reduce the probability of defect between the electrodes, consequently, construct more compact structure and achieve a board band absorption spectrum to obtain higher power conversion efficiency.

（5）Utilize the diversity of optical and electrical properties of different NPs to construct other functional photo-sensing nanodevices based on the developed process (ionic interaction system).

Therefore, it is important to cooperate with ***Professor Teng-Ming Chen's inorganic synthesis laboratory*** to develop more metal NPs (such as Cu NPs and Ag NPs) and semiconductor NPs (such as CdTe NPs and $TiO_2$ NPs). And then we can construct and measure different nanostructures composed of various NPs. In the nanodevice structure, the metal NPs are an important role to enhance the conductivity on the nanodevice and connect the CdSe/ZnS NPs. To improve the efficiency of large area, the size and sharp of metal NPs can be turned to enhance the density and conductivity of the metal. In the CdSe/ZnS NPs, we can use the photo-activated CdSe/ZnS NPs to enhance the quantum yield and photoluminescence.

（6）During the fabrication process, the defect between the electrodes is an very important problem. In order to reduce the probability of defect between the electrodes, the construction procedure must conduct carefully. However, the key point is the bonding between NPs and silicon oxide substrate. In this work, the chip was immersed in a 10% TMSPED/methanol solution that has two amino groups on one alkyl chain. The two amino groups caused the alkyl chain to repulse with each other, and consequently the distance between TMSPED molecules was relatively large. In order to increase the surface density of amino groups on the substrate, instead of modification by TMSPED, we used the APTES solution to modify the silicon oxide substrate with positive charges that has one amino group on one alkyl chain. Therefore, the repulsive force between the alkyl chains can be reduced significantly. To improve the compact structure, we can turn the fabrication conditions, such as low concentration QDs and low temperature, to build the layer-by-layer on the silicon oxide substrate.

（7）In this work, we have demonstrated the photo-sensing property of the nanodevices. The further works are to incorporate these inorganic nanodevices into nano-electronics system, like utilizing the current photo-sensing nanodevice based on NPs to construct two-dimensional photo-sensing system, a sensitive and multicolored photo-sensing system based on NPs on the silicon chip. Further applications and improvement on the proposed nanodevices are ongoing.