



# **ENHANCING PLASMONIC PHOTOVOLTAIC USING EMBEDDED METAL NANOPARTICLES**

By

**Marina Medhat Rassmi Melek**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfilment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
in  
**Engineering Physics**

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2017

# **ENHANCING PLASMONIC PHOTOVOLTAIC USING EMBEDDED METAL NANOPARTICLES**

By  
**Marina Medhat Rassmi Melek**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
in  
**Engineering Physics**

Under the Supervision of

**Prof. Alaa K. Abdelmageed**

Professor

Engineering Mathematics and Physics  
Department  
Faculty of Engineering, Cairo University

**Prof. Ezzeldin A. Soliman**

Professor and Chair

Physics Department  
School of Science and Engineering,  
American University in Cairo

**Dr. Yasser M. El-Batawy**

Associate Professor

Engineering Mathematics and Physics  
Department  
Faculty of Engineering, Other University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2017

# **ENHANCING PLASMONIC PHOTOVOLTAIC USING EMBEDDED METAL NANOPARTICLES**

By

**Marina Medhat Rassmi Melek**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfilment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
in  
**Engineering Physics**

Approved by the Examining Committee:

---

<b>Prof.Alaa K. Abdelmageed,</b>	Main Advisor
----------------------------------	--------------

---

<b>Prof.Ezzeldin A. Soliman,</b>	Advisor
(School of Science and Engineering, American University in Cairo)	

---

<b>Dr.Yasser M. El-Batawy,</b>	Advisor
--------------------------------	---------

---

<b>Prof.Adel Abdelkader Mohsen,</b>	Internal Examiner
-------------------------------------	-------------------

---

<b>Prof.Amr Mohamed Ali Shaarawi,</b>	External Examiner
(School of Science and Engineering, American University in Cairo)	

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2017

**Engineer's Name:** Marina Medhat Rassmi Melek  
**Date of Birth:** 28/09/1990  
**Nationality:** Egyptian  
**E-mail:** marinamedhat2011@gmail.com  
**Phone:** 01004473480  
**Address:** Engineering Mathematics and Physics  
Department, Cairo University,  
Giza 12613, Egypt  
**Registration Date:** 01/03/2014  
**Awarding Date:** ....../....../2017  
**Degree:** Master of Science  
**Department:** Engineering Mathematics and Physics



**Supervisors:**

Prof. Alaa K. Abdelmageed  
Prof. Ezzeldin A. Soliman  
Dr. Yasser M. El-Batawy  
(School of Science and  
Engineering, American  
University in Cairo)

**Examiners:**

Prof. Alaa K. Abdelmageed (Main Advisor)  
Prof. Ezzeldin A. Soliman (Advisor)  
Dr. Yasser M. El-Batawy (Advisor)  
Prof. Adel Abdelkader Mohsen (Internal Examiner)  
Prof. Amr Mohamed Ali Shaarawi (External Examiner)  
(School of Science and Engineering, American University in Cairo)

**Title of Thesis:**

Enhancing Plasmonic Photovoltaic Using Embedded Metal  
Nanoparticles

**Key Words:**

Photovoltaic; Plasmonic; Metal Nanoparticles; Nanoantennas; Plasmonic Solarcells

**Summary:**

Plasmonic Photovoltaic is a promising way to enhance the thin film photovoltaic (PV) efficiency. Gear shape nanoparticles are introduced to enhance the PV efficiency via increasing the power absorbed by the PV semiconductor in the visible and near infrared ranges. The modes of the gear nanoparticles are investigated. A parametric study is performed that demonstrates how the design parameters of the proposed nanoparticles can be engineered for best power absorption within Si. A Figure of Merit (FoM) is defined that consider all objectives. An optimization process is carried out and the optimum gear's dimensions, penetration depth, and periodicity are obtained for the maximum FoM. Then, a model for PIN-PV with embedded gear nanoparticles is presented for 1D and 2D structures. The enhancement of the embedded gear nanoparticles on the J-V characteristics of the PV is studied, and J-V characteristics corresponding to maximum FoM is presented.

# Acknowledgments

I would never have been able to finish my dissertation without the guidance of my committee members, help from friends, and support from my family.

First and foremost I offer my sincerest gratitude to my supervisors, Prof. Alaa K. Abdelmageed, Prof. Ezzeldin A. Soliman, and Dr. Yasser M. El Batawy who have supported me throughout my thesis with their patience and knowledge. I attribute the level of my Masters degree to their encouragement and effort and without them this thesis would not have been completed or written. One simply could not wish for a better or friendlier supervisors.

Besides my supervisors, I would like to thank my friends and fellow TAs; Mostafa Radwan , Ahmed Reda, Islam Hashem, Amr Mahmoud, Mohamed Zaghloul, Ahmed Yheia, and Islam Sayed for always been there for me showing their help and support.

Last but not the least, I would like to thank my family for giving birth to me at the first place and supporting me spiritually throughout my life.

Marina Medhat

*To my family and all my friends*

# Table of Contents

<b>Acknowledgments</b>	<b>i</b>
<b>Table of Contents</b>	<b>iii</b>
<b>List of Figures</b>	<b>v</b>
<b>List of Symbols and Abbreviations</b>	<b>ix</b>
<b>List of Publications</b>	<b>xii</b>
<b>Abstract</b>	<b>xiii</b>
<b>1 Introduction</b>	<b>1</b>
1.1 Motivation . . . . .	1
1.2 Photovoltaics (PV) Fundamentals . . . . .	1
1.3 Plasmonics Fundamentals . . . . .	2
1.4 Plasmonic Photovoltaics . . . . .	3
1.5 Thesis Objectives . . . . .	4
1.6 Thesis Structure . . . . .	5
<b>2 Plasmonic Nanoparticles</b>	<b>6</b>
2.1 Introduction . . . . .	6
2.2 Traveling versus Standing Wave Plasmonic Modes . . . . .	6
2.3 Proposed Plasmonic Gear Nanoparticle . . . . .	9
2.4 Parametric Study of the Gear Nanoparticle . . . . .	12
<b>3 Plasmonic Photovoltaic</b>	<b>19</b>
3.1 Introduction . . . . .	19
3.2 Absorption in Conventional PVs . . . . .	19
3.3 Absorption in Plasmonic PVs . . . . .	24

3.4	Figure of Merit (FoM) of Plasmonic PVs . . . . .	31
3.5	Optimum Design and Sensitivity Analysis . . . . .	37
<b>4</b>	<b>Photocurrent of Plasmonic PIN PV</b>	<b>41</b>
4.1	Introduction . . . . .	41
4.2	Theoretical Model: . . . . .	41
4.3	Photovoltaic Efficiency . . . . .	41
4.4	Photovoltaic Current . . . . .	43
4.5	Plasmonic Photovoltaic Current . . . . .	47
<b>5</b>	<b>Conclusion and Suggested Future Work</b>	<b>57</b>
5.1	Summary of research . . . . .	57
5.2	Suggested Future work . . . . .	57
	<b>References</b>	<b>59</b>
<b>A</b>	<b>PIN Mathematical Analysis</b>	<b>63</b>
A.1	Introduction . . . . .	63
A.2	Poisson's Equation . . . . .	63
A.3	Continuity Equation . . . . .	64
	A.3.0.1 For Electrons: . . . . .	64
	A.3.0.2 For Holes : . . . . .	64
A.4	Finite Difference Discritization . . . . .	66
	A.4.1 1D Meshing . . . . .	66
	A.4.2 2D Meshing . . . . .	70
A.5	NR Formula . . . . .	71



# List of Figures

1.1	Absorption Coefficient of Silicon . . . . .	2
1.2	Comparison between PN junction and PIN junction structure and Field . .	3
1.3	(a) Light trapping by nanoparticles from metal nanoparticles on the top surface of the solar cell. Light is scattered and trapped into the substrate at a higher angle, increasing the path length. (b) Light absorption enhancement in the semiconductor by embedded nanoparticles due to the enhanced near field of the nanoparticles. (c) Light trapping by coupling to guided modes of the solar cell from nanopatterned metallic back contacts.[18] . . . . .	4
2.1	Permittivity of the Aluminium, Copper, Gold, and Silver, versus the wavelength: (a) real part, $\epsilon'_r$ , and (b) imaginary part, $\epsilon''_r$ . . . . .	7
2.2	Surface Plasmon Polariton, i.e. surface wave mode. . . . .	8
2.3	Extinction cross-section of cube, disk, and sphere nanoparticles. . . . .	10
2.4	Geometry of the proposed gear nanoparticle. . . . .	11
2.5	Extinction cross-section versus wavelength for a gear nanoparticle with $D_1 = 80$ nm, $D_2 = 110$ nm, $\theta = 40^\circ$ , $\Phi = 45^\circ$ , and $T = 25$ nm surrounded by free-space. . . . .	11
2.6	Co-polar electric field distribution of a gear nanoparticle with dimensions $D_1 = 80$ nm, $D_2 = 110$ nm, $\theta = 40^\circ$ , $\Phi = 45^\circ$ , and $T = 25$ nm at $f = 485$ THz. (a) Top View, (b) Sectional View . . . . .	13
2.7	Co-polar electric field distribution of a gear nanoparticle with dimensions $D_1 = 80$ nm, $D_2 = 110$ nm, $\theta = 40^\circ$ , $\Phi = 45^\circ$ , and $T = 25$ nm at $f = 620$ THz. (a) Top View, (b) Sectional View . . . . .	14
2.8	Disk nanoparticle extinction cross-section versus wavelength with diameter $D = 110$ nm, and thickness of 25 nm. . . . .	14

2.9	Co-polar electric field distribution at $f = 605$ THz of a disk nanoparticle with dimensions $D = 110$ nm, and thickness of 26 nm. (a) Top View, (b) Sectional View . . . . .	15
2.10	Extinction cross-section spectrum of the gear nanoparticle with different inner diameters $D_1, D_2 = 110$ nm, $\theta = 40^\circ$ , $\Phi = 45^\circ$ , and $T = 25$ nm. . .	15
2.11	Extinction cross-section spectrum of the gear nanoparticle with different outer diameters $D_2, D_1 = 80$ nm, $\theta = 40^\circ$ , $\Phi = 45^\circ$ , and $T = 25$ nm. . . .	16
2.12	Extinction cross-section spectrum of the gear nanoparticle with different arm angle $\theta$ , $D_1 = 80$ nm, $D_2 = 110$ nm, $\Phi = 45^\circ$ , and $T = 25$ nm. . . .	17
2.13	Extinction cross-section spectrum of the gear nanoparticle with different gear thickness $T$ , $D_1 = 80$ nm, $D_2 = 110$ nm, $\Phi = 45^\circ$ , and $\theta = 40^\circ$ . . . .	17
3.1	Scattering Matrix Model (SMM). . . . .	22
3.2	S-parameters of a wave incident on Si block of thickness 100 nm. . . . .	23
3.3	Power absorption inside Si block of thickness 100 nm. . . . .	23
3.4	S-parameters of a wave incident on Si block with thickness 100 nm and backed by 50 nm silver plate. . . . .	24
3.5	Power absorption inside Si block with thickness 100 nm and backed by 50 nm silver plate. . . . .	25
3.6	S-parameters of a wave incident on Si block with thickness 100 nm , backed by 50 nm silver plate with, 20 nm glass cover. . . . .	25
3.7	Power absorption inside Si block with thickness 100 nm, backed by 50 nm silver plate with, 20nm glass cover. . . . .	26
3.8	S-parameters of a wave incident on Si block with thickness of 200 nm. . .	26
3.9	Power absorption inside Si block with thickness of 200 nm. . . . .	27
3.10	Gear nanoparticle embedded in Si block. . . . .	28
3.11	Total absorption of Si with gear nanoparticle of $D_1 = 40$ nm, $D_2 = 70$ nm, $\theta = 40^\circ$ , $\varphi = 45^\circ$ , $T = 25$ nm, and periodicity 200 nm versus wavelength. .	29
3.12	Comparison of the total absorption of Si only, Si with disks nanoparticles with $D = 70$ nm and Si with gear nanoparticles. . . . .	29
3.13	Solar spectrum irradiance. . . . .	30
3.14	Si absorption with embedded gear nanoparticle array with different penetration depth $d$ , $D_1 = 508$ nm, $D_2 = 556$ nm, $\theta = 31^\circ$ , $T = 40$ nm, and $P = 957$ nm: (a) without considering solar irradiance and (b) with considering solar irradiance. . . . .	32

3.15	Si absorption with embedded gear nanoparticle array with different periodicity $P$ , $D_1 = 508$ nm, $D_2 = 556$ nm, $\theta = 31^\circ$ , $T = 40$ nm, and $d = 15$ nm: (a) without considering solar irradiance and (b) with considering solar irradiance. . . . .	33
3.16	FoM versus inner diameter $D_1$ of a gear plasmonic PV with $D_2 = 556$ nm, $T = 40$ nm, $\theta = 40^\circ$ , $d = 15$ nm, and $P = 957$ nm. . . . .	34
3.17	FoM versus outer diameter $D_2$ of a gear plasmonic PV with $D_1 = 508$ nm, $T = 40$ nm, $\theta = 40^\circ$ , $d = 15$ nm, and $P = 957$ nm. . . . .	34
3.18	FoM versus arm angular span of a gear plasmonic PV with $D_1 = 508$ nm, $D_2 = 556$ nm, $T = 40$ nm, $d = 15$ nm, and $P = 957$ nm. . . . .	35
3.19	FoM versus particle thickness $T$ of a gear plasmonic PV with $D_1 = 508$ nm, $D_2 = 556$ nm, $\theta = 31^\circ$ , $d = 15$ nm, and $P = 957$ nm. . . . .	35
3.20	FoM versus penetration depth $d$ of a gear plasmonic PV with $D_1 = 508$ nm, $D_2 = 556$ nm, $\theta = 31^\circ$ , $T = 40$ nm, and $P = 957$ nm. . . . .	36
3.21	FoM versus periodicity $P$ of a gear plasmonic PV with $D_1 = 508$ nm, $D_2 = 556$ nm, $\theta = 31^\circ$ , $T = 40$ nm, and $d = 15$ nm. . . . .	36
3.22	FoM versus iterations. . . . .	37
3.23	Si absorption with and without optimum gear nanoparticles array with $D_1 = 505.6$ nm, $D_2 = 583.62$ nm, $\theta = 38^\circ$ , and $T = 48.24$ nm, $d = 14.064$ nm, and $P = 878.4$ nm. . . . .	38
3.24	Si absorption with optimum gear nanoparticles array and the corresponding disk nanoparticles array with the same outer diameter, penetration depth, and periodicity. . . . .	39
3.25	Extinction cross-section of the optimum gear nanoparticles array and the corresponding disk nanoparticles array with the same outer diameter, penetration depth, and periodicity. . . . .	39
4.1	PIN junction structure. . . . .	42
4.2	Energy band diagram of P-type, intrinsic, and N-type semiconductor (a) Isolated (b) combined in PIN junction in equilibrium. . . . .	42
4.3	Electric potential for PIN PV under no illumination. . . . .	47
4.4	Electric Field for PIN PV at equilibrium (a) for 1D model (b) for 2D model. . . . .	48
4.5	Electric potential for PIN PV under illumination with $G_0 = 1.4 \times 10^{27} \text{ cm}^{-3} \text{ sec}^{-1}$ . . . . .	49
4.6	Electric Field for PIN PV under illumination (a) for 1D model (b) for 2D model with $G_0 = 1.4 \times 10^{27} \text{ cm}^{-3} \text{ sec}^{-1}$ . . . . .	50

4.7	(a) Electric potential for PIN PV for dark and under illumination with $G_0 = 1.4 \times 10^{27} \text{ cm}^{-3} \text{ sec}^{-1}$ (b) Electric Field for PIN PV for dark and under illumination with $G_0 = 1.4 \times 10^{27} \text{ cm}^{-3} \text{ sec}^{-1}$ . . . . .	51
4.8	Comparison between the presented model and nanoHUB results under no-illumination for (a) the potential (b) the electric field. . . . .	52
4.9	J-V Characteristics for different values of $D_1$ of gear nanoparticles with $D_2$ is 556 nm, $\theta$ is $31^\circ$ , and thickness $T$ is 40 nm embedded in the PV. . .	53
4.10	J-V Characteristics for different values of $D_2$ of gear nanoparticles with $D_1$ is 508 nm, $\theta$ is $31^\circ$ , and $T$ is 40 nm embedded in the PV. . . . .	53
4.11	J-V Characteristics for different values of $\theta$ of gear nanoparticles with $D_1$ is 508 nm, $D_2$ is 556 nm, and $T$ is 40 nm embedded in the PV. . . . .	54
4.12	J-V Characteristics for different values of $T$ of gear nanoparticles with $D_1$ is 508 nm, $D_2$ is 556 nm, and $\theta$ is $31^\circ$ embedded in the PV. . . . .	54
4.13	J-V Characteristics for different values of $d$ of gear nanoparticles with $D_1 = 508 \text{ nm}$ , $D_2 = 556 \text{ nm}$ , $\theta = 31^\circ$ , and $T = 40 \text{ nm}$ embedded in the PV. . . . .	55
4.14	J-V Characteristics for different values of $P$ of gear nanoparticles with $D_1 = 508 \text{ nm}$ , $D_2 = 556 \text{ nm}$ , $\theta = 31^\circ$ , and $T = 40 \text{ nm}$ embedded in the PV. . . . .	56
4.15	J-V curve at optimum dimensions of gear nanoparticle $D_1 = 505.6 \text{ nm}$ , $D_2 = 583.62 \text{ nm}$ , $\theta = 38^\circ$ , and $T = 48.24 \text{ nm}$ and optimum position at $d = 14.064 \text{ nm}$ , and $P = 878.4 \text{ nm}$ embedded in PIN-PV. . . . .	56
A.1	1D Meshing . . . . .	67
A.2	2D Meshing . . . . .	69

# List of Symbols and Abbreviations

<b>a-si</b>	Amorphous silicon.
<b>AlGaAs</b>	Aluminum Galium Arsenide.
<b>c-si</b>	Crystalline silicon.
<b>GaN</b>	Galium nitride.
<b>InGaAs</b>	Indium Galium Arsenide.
<b>InGaP</b>	Indium Galium Phosphide.
$\epsilon$	Dielectric constant.
$\Gamma$	collision frequency.
$\lambda$	Optical wavelength.
$\mu_n$	Average Electron mobility .
$\mu_p$	Average Hole mobility .
$\omega_p$	plasma frequency of the free electron gas.
$\omega$	Angular frequency.
$\phi_n$	N-type semiconductor work function.
$\phi_p$	P-type semiconductor work function.
$\Phi$	Work function.
$\psi$	Potential.
$\rho$	Charge density.
$\tau_n$	Electrons life time.
$\tau_p$	Holes lifetime.
$c$	Speed of light.
$D_n$	Electrons diffusion constant.
$D_p$	Holes diffusion constant.

$e, q$	Electron charge.
$E_f$	Fermi level.
$E$	Electric field.
$G$	Generation rate.
$H$	Magnetic field.
$h$	Planks constant.
$K$	Boltzmann constant.
$m$	Mass of electrons.
$N_a$	Acceptor doping concentration.
$N_d$	Donner doping Concentration.
$n_i$	Intrinsic carrier concentration.
$N$	number of electrons per unit volume.
$n$	Electron Concentration.
$P_{abs}$	Absorped Power in Si.
$P_L$	Absorped Power.
$p$	Holes Concentration.
$R$	Shockley Read Hall recombination rate.
$S_{11}$	Power reflected.
$S_{21}$	Power transmited.
$S$	Solar spectrum irradiace for AM1.5 .
$T$	Temperature in Kelvin scale.
$\theta$	Gear arm angle.
$D_1$	Inner diameter.
$D_2$	Outer diameter.
$d$	Nanoparticle depth from Si surface.
$P$	Structure periodicity.
$S_g$	Global scattering matrix.
$T_{Si}$	Silicon thickness.
<b>AD</b>	anno Domini.

<b>NanoHUB</b>	In-browser simulation tools geared toward nanotechnology, electrical engineering, chemistry, and semiconductor education.
<b>NR</b>	Newton- Raphson algorithm.
<b>PV</b>	Photovoltaic.
<b>SOI</b>	silicon on insulator.
<b>THz</b>	Terahertz.
<b>TW</b>	terawatts.