

Implementation of Metallic Plasmon Nanostructures to Enhance Sunlight Absorption in Thin Photovoltaic III-V Semiconductor Compound Solar Cells

Nadereh Tabrizi

Department of Physics, Payam e Noor University, P.O. Box 19395-3697, Tehran, Iran

Abstract: Solar cells are known as reproducible, carbon-free electric energy resource to reduce the utilization of fossil fuel. Recently, around 40% energy conversion yield have been gained in laboratories using III-V semiconductor compounds as photovoltaic materials. One of the efforts and accomplishments done for higher efficiency III-V semiconductor compound solar cells with metallic plasmonstructures is declared, in this study Technological strategies for further performance improvement from the mostefficient (Al) In GaP/(In) GaAs/Ge triple-junction cells considering 1.0 eV band gap semiconductors are discussed. By adding metallic plasmonnano structures, we couldretouch photonic energy flow directions to increase sunlight absorption in thin photovoltaic semiconductor materials.

Key words: Solar energy, solar cells, photovoltaics, semiconductors, sunlight absorption enhancement

INTRODUCTION

The actual world use of electric energy is around 12-13 TW and the earth receives moresolar energy in one hour than the energy used globally in one year, considering the solar constant 1.7×10^5 TW at the top of the earth's atmosphere (Nozik, 2005). TheWorld Energy Council (WEC, 2013) sees world electricity consumption increasing to >40,000 TWh/a in 2040. The fossil part of generation depends on energy policy. It can stay around 70% in the so-called Jazz scenario where countries rather independently "improvise" but it can also decrease to around 40% in the Symphony scenario if countries work orchestrated for more climate friendly policy. However, the solar energy diffusion, around 1 kW m^{-2} is quite thin and thus a huge area of energy converters would be needed to meet theworld's energy usage. Therefore high performance solar energy conversion is deterministic. Asolar cell, orphotovoltaic cellin very early days also termed solar battery (Shockley and Queisser, 1961) is an electrical device that converts the energy of light directly in to electricity by the photo voltaic effect which is a physical and chemical phenomenon (Anonymous, 2015). It is a form of photoelectric cell, defined as a device whose electrical characteristics, such as current, voltage or resistance, vary when exposed to light. Solar cells are the building blocks of photovoltaic modules, otherwise known assolar panels. Concentrating Solar Power has several advantages over photovoltaic by having higher efficiencies, lower investment costs and an inherent thermal storage capacity that enables power generation during cloud cover or after sunset and a better hybrid

operation capability with other fuels to meet base-load demand at night. Establishing a concentrating solar power plant creates jobs and helps develop existing local industries. This together with the potential for niche applications such as absorption chilling make concentrating solar power a rational choice in tackling Bangladesh's energy crisis and fulfilling its renewable energy goals. Electron-hole pairs are produced by the energy of the incident photons dominating the energy bandgap of the photovoltaic material tomake a current flow according to the built-in potential slope in the material. Solar cells are promising as a carbon-free energy source to suppress the global warming. In laboratories the highest reported cell efficiencies are just declared around 40% while the energy conversionefficiencies for thermal power generation can enhance to 50%. This fact, although does not mean thatthermal generation is better due to its resources such as fossil fuels are limited while solar energy is unlimited (Emery and Osterwald, 1986; Nann and Emery,1992).

Solar cells made of III-V semiconductor compounds are examined in this articlebecause the leading energy conversion efficiencies have been displayed by these types ofsolar cells, rather than the other materials represented by silicon (Green *et al.*, 2009). In addition, III-V semiconductor compoundmaterials have advantages including the band gap tunability by elemental compositions, higher photonabsorption by the direct bandgap energies, higher resistivity against high-energy rays in space and lower efficiency degradation by heat than Si solar cells. The energy conversion efficiencies of III-V solar cells have been steadily increasing so far

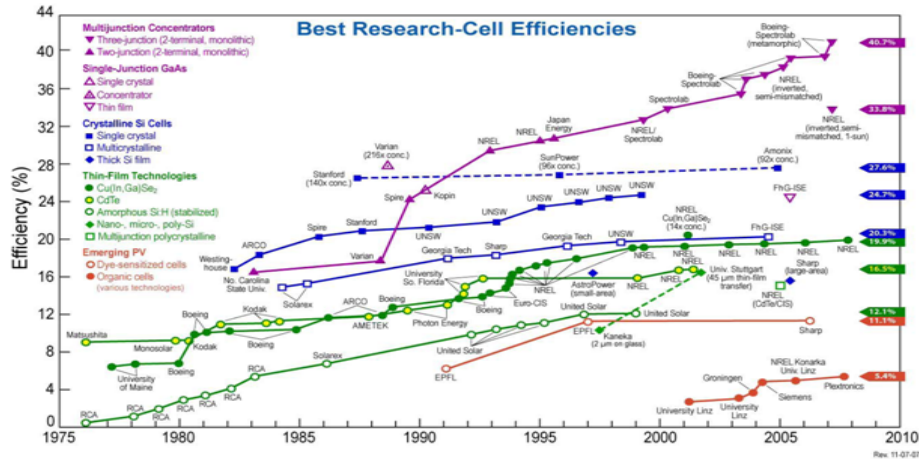


Fig. 1: Reported timeline of solar cell energy conversion efficiencies (National Renewable Energy Laboratory)

Fig. 1. Reported timeline of solar cell energy conversion efficiencies (National Renewable Energy Laboratory) and are approaching 40% for the laboratory-scale cells. One of key factors which recently being studied intensively for performance enhancement of III-V semiconductor compound solar cells, addressed in this article. Emerging solar cells with metallic plasmon nano structures retouching photonic energy flow directions to enhance sunlight absorption in thin photovoltaic semiconductor materials is discussed (Fig. 1).

USAGE OF PLASMON NANO METALLIC STRUCTURES IN ORDER TO IMPROVE THE LIGHT ABSORPTION

Scattering and absorption depend on the size of the particles. Metallic particles that are much smaller than the wavelength of light tend to absorb more and hence extinction is dominated by absorption in the metal particles. Absorption dissipates heat and this property is utilized in applications like solar glazing, nano scale lithography and therapeutic applications (Cortie *et al.*, 2005; Pissuwan *et al.*, 2006) (Fig. 2).

Metal nanoparticles are recognized to exhibit distinctive optical characteristics such as Surface Enhanced Raman Scattering (SERS) and second harmonic generation (SHG), relative to the bulk form of metals (Chen *et al.*, 1981; Wokaun *et al.*, 1981; Garcia-Vidal and Pendry 1996). Representatives of the use of metal nanoparticles are biomolecular manipulation, labeling and detection with SERS (Cao *et al.*, 2002; Fritzsche and Taton, 2003). These characteristics highly rely on the surface plasmon absorption, an enhanced absorption of light or electromagnetic fields by coupling between the incident photons and collective oscillation of free electrons at the metal surface (Maier and Atwater, 2005; Atwater, 2007).

Electromagnetic energy was theoretically suggested that can be guided along periodic chain arrays of closely spaced metal nanoparticles that transform the optical mode into non-radiating surface plasmons (Quinten *et al.*, 1998). Such plasmon devices exploit light localization in the dipole-dipole coupling or collective dipole plasmon oscillations of electrons, in neighboring nanoscale metal particles at the plasmon frequency. Also, light can be routed efficiently around sharp corners of nanoparticle chain arrays (Maier *et al.*, 2002). Such plasmon waveguide technologies can potentially be utilized for construction of all-optical nanoscale network (Barnes *et al.*, 2003; Dobrzynski *et al.*, 2004; Pacifici *et al.*, 2007; Kaya *et al.*, 2012).

Thinner photovoltaic layers will have less light absorption while thicker layers will have more bulk carrier recombination as schematically depicted in Fig. 3. Both of these two factors would be losses for the solar cell electrical output converted from the incident sunlight energy.

With active layer thickness optimization, PCE of the organic solar cells was increased from 0.56% (Kaya *et al.*, 2012) to 1.06%. IPCE of the solar cells was measured and the best efficiency was found as 51%. Finally it was seen that hole mobilities of the solar cells are highly dependent on the active layer thickness and obey Child's Law. The best mobility was obtained for the active layer coating with 100 nm (Apaydin *et al.*, 2013). Therefore the thickness of the active photovoltaic layer is usually optimized to maximize the energy conversion efficiency through that trade-off.

Metallic nanostructures can excite surface plasmons and can dramatically increase the optical path length in thin active photovoltaic layers to enhance overall photoabsorption.

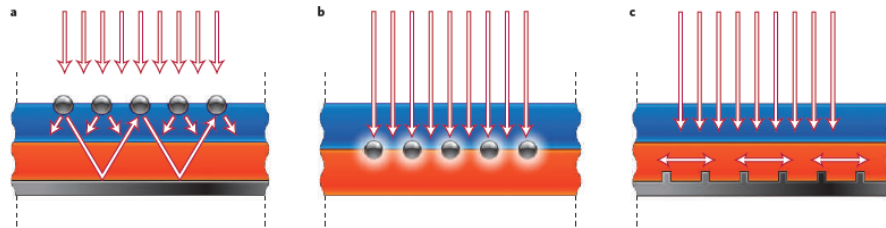


Fig. 2: Plasmonic light-trapping geometries for thin-film solar cells; a, Light trapping by scattering from metal nanoparticles at the surface of the solar cell. Light is preferentially scattered and trapped into the semiconductor thin film by multiple and high-angle scattering, causing an increase in the effective optical path length in the cell; b, Light trapping by the excitation of localized surface plasmons in metal nanoparticles embedded in the semiconductor. The excited particles' near-field causes the creation of electron-hole pairs in the semiconductor; c, Light trapping by the excitation of surface Plasmon polaritons at the metal/semiconductor interface. A corrugated metal back surface couples light to surface Plasmon polariton or photonic modes that propagate in the plane of the semiconductor layer (Harry, 2010)

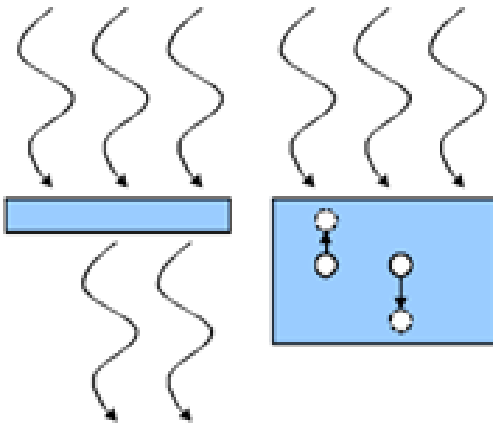


Fig. 3: Trade-off issue in photovoltaic layer thickness Schematically

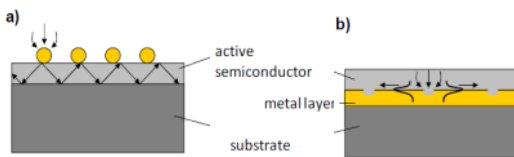


Fig. 4: Cross-sectional of solar cell structures schematically with: a) metal nanoparticles on top and b) a back metal layer

Metal nanoparticles inserted in solar cell surfaces can act as “antennas” to collect the incident light with their large extinction cross section near the surface plasmon resonance and then scatter the incident light into a vast range of angles to increase the optical path length in the absorber layer (Fig. 4a). This effect has potential for cell cost and weight reduction due to use of thinner absorber layers and also for efficiency enhancement associated with increased carrier excitation level. Much higher optical

scattering rates over absorption rates can be gained for noble metal particles to minimize absorption loss by properly choosing particles' diameters, around 100 nm as a rule of thumb. The ratio of scattering/absorption rates becomes larger for larger particles in the quasistatic limit approximation valid for subwavelength-scale particles, while particles with sizes comparable to or larger than incident wavelengths would suffer from electrodynamic damping to lose the solar energy just as heat generated in the particles. Several research groups have observed photocurrent increase for Si cells by this scheme (Stuart and Hall, 1996; Schaadt *et al.*, 2005; Pillai *et al.*, 2006; Derkacs *et al.*, 2006; Catchpole and Pillai, 2006; Pillai *et al.*, 2007).

By attaching a metallic layer at the bottom of a photovoltaic layer as schematically depicted in Fig. 4b, incident light can couple into surface plasmons propagating at the semiconductor/metal interface via some subwavelength-size feature such as nanoscale grooves (Pacifci *et al.*, 2007; Lezec and Thio 2004; Gay *et al.*, 2006; Chen *et al.*, 2006).

In this way, we can convert the direction of energy flux from normal to lateral direction relative to the photovoltaic layer. This is a novel concept to utilize such surface plasmon propagation for solar cell applications to harvest more energy from the sun in thin photovoltaic active layers (Tanabe *et al.*, 2008; Ferry *et al.*, 2008). Some types of conventional solar cells such as silicon solar cells also have metallic back reflectors to increase optical path, while III-V semiconductor compound solar cells such as GaAs cells have thin photovoltaic active layers on top of thick substrate. However, the plasmon-induced absorption enhancement by metallic back structures observed in this study would occur significantly only for strongly absorbing or direct bandgap semiconductors accounting for the energy dissipation in metals.

A calculation for energy dissipation fraction of coupled surface Plasmon polarities propagating at material interfaces into metals and semiconductors showed that most energy is absorbed by GaAs rather than metals for the visible optical wavelength range which solar cell applications concerns, particularly for the cases with (Tanabe, 2008). The results illustrate a reasonable accuracy in comparison to Mehrian's studies (Nowruzpour Mehrian and Naei, 2013; Nowruzpour Mehrian *et al.*, 2013, 2014; Vaziri, 2015). This result means GaAs can effectively harvest the energy extracted from the coupled surface plasmons beating the Ohmic loss in metals with its strong absorption or large imaginary part of dielectric function. On the other hand, silicon which is a weak absorber has much lower energy absorption fraction suffering from Ohmic loss in metals. This is a great benefit for direct bandgap semiconductor materials which are stronger absorbers, for such types of "plasmon" solar cell applications.

CONCLUSION

One of recent developments in the field of III-V semiconductor compound photovoltaics were discussed in the very article and possible strategies for further efficiency improvements were introduced. Therefore metal nanoparticles and metallic thin films with subwavelength-scale grooves are supposed to assist sunlight absorption in thin film photovoltaics with surface plasmon resonance.

REFERENCES

- Anonymous, 2015. Solar cells. <http://www.chemistryexplained.com/Ru-Sp/Solar-Cells.html>.
- Apaydin, D.H., D.E. Yildiz, A. Cirpan and L. Toppare, 2013. Optimizing the organic solar cell efficiency: Role of the active layer thickness. *Solar Energy Mater. Solar Cells*, 113: 100-105.
- Atwater, H.A., 2007. The promise of plasmonics. *Scient. Am.*, 296: 56-62.
- Barnes, W.L., A. Dereux and T.W. Ebbesen, 2003. Surface plasmon subwavelength optics. *Nature*, 424: 824-830.
- Cao, Y.C., R. Jin and A.C. Mirkin, 2002. Nanoparticles with raman spectroscopic fingerprints for DNA and RNA detection. *Science*, 297: 1536-1540.
- Catchpole, K.R. and S. Pillai, 2006. Absorption enhancement due to scattering by dipoles into silicon waveguides. *J. Applied Phys.*, Vol. 100, No. 4. 10.1063/1.2226334
- Chen, C.K., A.R.B. de Castro and Y.R. Shen, 1981. Surface-enhanced second-harmonic generation. *Phys. Rev. Lett.*, 46: 145-148.
- Chen, L., J.T. Robinson and M. Lipson, 2006. Role of radiation and surface plasmon polaritons in the optical interactions between a nano-slit and a nano-groove on a metal surface. *Opt. Express*, 14: 12629-12636.
- Cortie, M.B., X. Xu, H. Chowdhury, H. Zareie and G. Smith, 2005. Plasmonic heating of gold nanoparticles and its exploitation. *Proceedings of the SPIE Symposium on Smart Structures, Devices and Systems II*, December 12-15, 2005, Sydney, Australia, pp: 565-573.
- Derkacs, D., S.H. Lim, P. Matheu, W. Mar and E.T. Yu, 2006. Improved performance of amorphous silicon solar cells via scattering from surface plasmon polaritons in nearby metallic nanoparticles. *Applied Phys. Lett.*, Vol. 89, No. 9. 10.1063/1.2336629
- Dobrzynski, L., A. Akjouj, B. Djafari-Rouhani, J.O. Vasseur and M. Bouazaoui *et al.*, 2004. Simple nanometric plasmon multiplexer. *Phys. Rev. E*, Vol. 69, No. 3. 10.1103/PhysRevE.69.035601
- Emery, K.A. and C.R. Osterwald, 1986. Solar cell efficiency measurements. *Solar Cells*, 17: 253-274.
- Ferry, V.E., L.A. Sweatlock, D. Pacifici and H.A. Atwater, 2008. Plasmonic nanostructure design for efficient light coupling into solar cells. *Nano Lett.*, 8: 4391-4397.
- Fritzsche, W. and T.A. Taton, 2003. Metal nanoparticles as labels for heterogeneous, chip-based DNA detection. *Nanotechnology*, 14: R63-R73.
- Garcia-Vidal, F.J. and J.B. Pendry, 1996. Collective theory for surface enhanced Raman scattering. *Phys. Rev. Lett.*, 77: 1163-1166.
- Gay, G., O. Alloschery, B.V. de Lesegno, C. O'Dwyer, J. Weiner and H.J. Lezec, 2006. The optical response of nanostructured surfaces and the composite diffracted evanescent wave model. *Nat. Phys.*, 2: 262-267.
- Green, M.A., K. Emery, Y. Hishikawa and W. Warta, 2009. Solar cell efficiency tables (version 33). *Progr. Photovoltaics: Res. Applic.*, 17: 85-94.
- Kaya, E., D.H. Apaydin, D.E. Yildiz, L. Toppare and A. Cirpan, 2012. Solution processable benzotriazole and fluorene containing copolymers for photovoltaic applications. *Solar Energy Mater. Solar Cells*, 99: 321-326.
- Lezec, H. and T. Thio, 2004. Diffracted evanescent wave model for enhanced and suppressed optical transmission through subwavelength hole arrays. *Opt. Express*, 12: 3629-3651.
- Maier, S.A. and H.A. Atwater, 2005. Plasmonics: Localization and guiding of electromagnetic energy in metal/dielectric structures. *J. Applied Phys.*, Vol. 98, 10.1063/1.1951057.

- Maier, S.A., M.L. Brongersma and H.A. Atwater, 2002. Electromagnetic energy transport along Yagi arrays. *Mater. Sci. Eng.: C*, 19: 291-294.
- Nann, S. and K. Emery, 1992. Spectral effects on PV-device rating. *Solar Energy Mater. Solar Cells*, 27: 189-216.
- Nowruzpour Mehrian, S.M. and M.H. Naei, 2013. Two dimensional analysis of functionally graded partial annular disk under radial thermal shock using hybrid Fourier-Laplace transform. *Applied Mech. Mater.*, 436: 92-99.
- Nowruzpour Mehrian, S.M., A. Nazari and M.H. Naei, 2014. Coupled thermoelasticity analysis of annular laminate disk using Laplace transform and Galerkin finite element method. *Applied Mech. Mater.*, 656: 298-304.
- Nowruzpour Mehrian, S.M., M.H. Naei and S.Z. Mehrian, 2013. Dynamic response for a functionally graded rectangular plate subjected to thermal shock based on LS theory. *Applied Mech. Mater.*, 332: 381-395.
- Nozik, A.J., 2005. Exciton multiplication and relaxation dynamics in quantum dots: Applications to ultrahigh-efficiency solar photon conversion. *Inorg. Chem.*, 44: 6893-6899.
- Pacifici, D., H.J. Lezec and H.A. Atwater, 2007. All-optical modulation by plasmonic excitation of CdSe quantum dots. *Nat. Photon.*, 1: 402-406.
- Pillai, S., K.R. Catchpole, T. Trupke and M.A. Green, 2007. Surface plasmon enhanced silicon solar cells. *J. Applied Phys.*, Vol. 101, No. 9. 10.1063/1.2734885.
- Pillai, S., K.R. Catchpole, T. Trupke, G. Zhang, J. Zhao and M.A. Green, 2006. Enhanced emission from Si-based light-emitting diodes using surface plasmons. *Applied Phys. Lett.*, Vol. 88, No. 16. 10.1063/1.2195695.
- Pissuwan, D., S.M. Valenzuela and M.B. Cortie, 2006. Therapeutic possibilities of plasmonically heated gold nanoparticles. *Trends Biotechnol.*, 24: 62-67.
- Quinten, M., A. Leitner, J.R. Krenn and F.R. Aussenegg, 1998. Electromagnetic energy transport via linear chains of silver nanoparticles. *Opt. Lett.*, 23: 1331-1333.
- Schaadt, D.M., B. Feng and E.T. Yu, 2005. Enhanced semiconductor optical absorption via surface plasmon excitation in metal nanoparticles. *Applied Phys. Lett.*, Vol. 86, No. 6. 10.1063/1.1855423.
- Shockley, W. and H.J. Queisser, 1961. Detailed balance limit of efficiency of p-n junction solar cells. *J. Applied Phys.*, 32: 510-519.
- Stuart, H.R. and D.G. Hall, 1996. Absorption enhancement in silicon-on-insulator waveguides using metal island films. *Applied Phys. Lett.*, 69: 2327-2329.
- Stuart, H.R. and D.G. Hall, 1998. Island size effects in nanoparticle-enhanced photodetectors. *Applied Phys. Lett.*, 73: 3815-3817.
- Tanabe, K., 2008. Low-cost high-efficiency solar cells with wafer bonding and plasmonic technologies. Ph.D. Thesis, California Institute of Technology, Pasadena, CA., USA.
- Tanabe, K., K. Nakayama and H.A. Atwater, 2008. Plasmon-enhanced absorption and photocurrent in ultrathin GaAs solar cells with metallic nanostructures. *Proceedings of the 33rd IEEE Photovoltaic Specialists Conference*, May 11-16, 2008, San Diego, CA., USA., pp: 1-4.
- Vaziri, M.R., S.N. Mehrian, M.H. Naei and J.Y.S. Ahmad, 2015. Modification of shock resistance for cutting tools using functionally graded concept in multilayer coating. *J. Thermal Sci. Eng. Applic.*, Vol. 7, No. 1. 10.1115/1.4028982.
- WEC., 2013. World energy scenarios: Composing energy futures to 2050. World Energy Council, London, United Kingdom.
- Wokaun, A., J.G. Bergman, J.P. Heritage, A.M. Glass, P.F. Liao and D.H. Olson, 1981. Surface second-harmonic generation from metal island films and microlithographic structures. *Phys. Rev. B*, 24: 849-856.