Chapter 6
Optical Nano–Antennas for Energy Harvesting

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ABSTRACT

The solar energy is able to supply humanity energy for almost another 1 billion years. Optical nano-antennas (ONAs) are an attractive technology for high efficiency, and low-cost solar cells. These devices can be classified to semiconductor nano-wires and metallic nano-antenna. Extensive studies have been carried out on ONAs to investigate their ability to harvest solar energy. Inspired by these studies, the scope of the chapter is to highlight the latest designs of the two main types of ONAs. The metallic nano-antennas are discussed based on the following points: plasmon, modeling, and performance of antenna designs using different configurations and materials. Moreover, the semiconductor nano-wires are studied thoroughly in terms of photonic crystals, antenna design with different patterns, nano-wire forms and materials. Also, the applications of ONAs and their fabrication aspects such as diode challenges are presented in detail. Finally, three novel designs of ONAs are presented and numerically simulated to maximize the harvesting efficiency.

INTRODUCTION

The search for alternative energy sources in the 21st century is a growing academic and industrial pursuit. Rising costs of carbon-based fuels coupled with increased emissions has placed a greater demand on the clean energy sector. Recently, renewable energy gives strong contributions to power generation without increasing environmental pollutions. A promising energy source is photovoltaics (PVs), which has traditionally been made from high purity, expensive crystalline silicon (c-Si). In addition, the PV solar cell devices are designed to absorb solar energy in the visible region (400 nm-700 nm) which constitutes 46%

of the solar spectrum (Malinovska, 2010). Therefore, the search for cheaper, high-performance materials for solar cells based applications is mandatory.

One of the alternative approaches to PV technology is the optical antennas that can harvest more solar energy by extending the absorbed range to the infrared (IR) region (Malinovska, 2010). The optical antenna can be fabricated by using metallic nano-particles or semiconductor nano-wires. Therefore, the optical antenna can be classified to metallic nano-antenna (rectenna) and semiconductor nano-antenna. The use of rectenna for energy harvesting depends on the fact that when an electromagnetic wave is incident on a nano-antenna, a time varying current will be induced on the antenna surface, and hence a voltage will be generated at the feeding point of the antenna. The generated wave will oscillate at the frequency of the incident wave. Consequently, in order to obtain Direct Current (DC) power, a suitable rectifier should be embedded at the feed point of antenna. These types of energy harvesting systems are called "rectennas"; which basically consist of antennas connected to a rectifier that converts the received signal to DC power and produces electricity (Malinovska 2010; Berland *et al.* 2001). An infrared rec-tenna structures based on metal–insulator–metal (MIM) diodes between dipoles (Berland *et al.*, 2003) has been designed for operation at the operating wavelength $\lambda=10$ μm. However the efficiency of this system was less than 1% (Berland *et al.*, 2003). A spiral nano-antenna for solar energy harvesting has been designed and fabricated at mid-infrared region by Kotter *et al*. (2010). In addition, Midrio *et al*. (2011) have designed and analyzed mono pole antenna based on nickel for the reception of thermal radiation. Vandenbosch *et al*. (2012) have introduced upper bounds for the solar energy harvesting efficiency of metallic nano-antennas. In this regard the silver exhibited the highest efficiencies, both in free space and on top of glass (SiO_2) substrate, with radiation efficiencies near or slightly above 90% (Vandenbosch *et al.*, 2012). Although, the metallic nano-antenna offers outstanding harvesting efficiency over a wide frequency range, no suitable rectifier diodes are described in the literature to meet the requirements for solar energy harvesting.

Semiconductor nano-antennas have recently gained tremendous interest due to their light absorption (Hong *et al.*, 2013). Light absorption in standing semiconductor nanowires is a complex phenomenon, with strong dependence on nano-wire dimensions, lattice arrangement and absorption coefficient of the raw materials (Hong *et al.*, 2013). Ordered semiconductor nano-antenna structure can be fabricated through a few unattractive methods, such as lithography and polystyrene ball assembly, due to their high cost and complexity (Hong *et al.*, 2013).

Following this introduction, a detailed description of the science, concepts of design, modeling key issues and the history of optical nano-antenna (ONA) solar cells will be provided. In addition, the latest designs and fabrication challenges of the two types of optical nano-antennas are discussed thoroughly. On top of that, three novel designs of flower shaped metallic nano-antenna, decagonal semiconductor nano-wires with semiconductor and hybrid cores are presented and analyzed using 3D full vectorial finite difference method (FDTD) (Taflove & Hagness, 2005). The performance of the suggested ONAs with different materials and configurations has been investigated based on the absorption efficiency spectra, absorbed power profiles and emission patterns. The proposed flower shaped design exhibits higher efficiency over the conventional dipole antenna by at least 15%. In addition, the total harvesting efficiency is enhanced by 32.7%. Moreover, the suggested nano-antenna offers large bandwidth in the wavelength range from 450 nm to 1400 nm. Additionally, the flower-shaped dipole nano-antenna has better efficiency of 74.6% compared to the conventional solar cells at $\lambda= 500$ nm at which the sun irradiance is maximum. Furthermore, the calculated ultimate efficiency of the proposed D-SiNWs with solid semiconductor core is 19.3%. This ultimate efficiency can be maximized either by tuning the geometric parameters of

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