Smart electricity grids with high efficiency plasmonics-based solar cells

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ABSTRACT

This paper presents an improvement method for future smart electricity grid performance using high efficiency solar cells. The smart grid offers several advantages for the connection of solar (renewable) energy sources to provide an efficient operation and better performance of the power systems. Finite-difference time domain (FDTD) method is employed to simulate the light transmission, reflection and absorption of high efficiency solar cell structures. Simulation results show that the reflection loss is reduced with the use of nanostructures compared with the flat type substrates. Therefore, the proposed solar cells will inject more energy into the electricity grid and hence improving the overall system performance.

Introduction

Smart grid is one of the most promising technology for retaining high quality performance of power systems. It can predict and intelligently respond to the behaviour and actions of all electric power users connected to the grid including suppliers and consumers in order to efficiently deliver reliable, economic and sustainable electricity services [1]. The generation and transmission networks have some degree of automation with supervisory control and data acquisition (SCADA) system that is connected with various components through telecommunication links, such as, microwave links and fiber optics to maintain the system security and facilitate the integrated operation safely [2-5].

The distribution system and the demand side are mainly passive with little communication to or from the customers. Worldwide, there has been an interest in decarbonising the electrical energy sector while minimizing the dependency on imported fossil fuel. This will require harnessing all possible renewable energy sources while promoting energy efficiency and conservation. This new environment will require an extensive use of modem information and communication technologies together with sensors, smart meters, fast simulation and modelling platforms and power electronics from the supply side to demand side. The name "Smart Grid" has become common to describe this future power networks [1-5]. As reserves of fossil fuels are used up, the need to find alternative natural sources for clean energy generation, such as, solar, hydroelectric, wind and biomass renewable energy sources that can be used in a wide range of applications from heating water and generating electricity to telecommunications and transportation has become very essential. Solar cell is a very promising renewable and green energy source. Since its discovery in the nineteenth century, scientists and researchers have been trying to improve its current conversion efficiency [6]. Recently, the metallic nanostructure devices have been identified as promising candidates for realising high-efficiency solar (photovoltaic) cells. These nanostructures enable strong interaction between the light and metallic nanostructures and could, therefore, enhance the trapping of incident sun (solar)

light inside the thin-film of the solar cell. As the conventional solar cell efficiency is low, it is necessary to improve the conversion efficiency [7-11]. This paper introduces a new approach to improve the performance of electricity grids using the high efficiency solar cells. The approach relies on the addition of a layer on the top of the existing solar cells that will improve its conversion efficiency. This additional layer will provide an effect which is called "plasmonics". The term "plasmonics" is the exploitation of the optical properties of surface plasmons in metals for local field enhancement and radiation confinement. The plasmons can couple with light and concentrate the energy into very small areas [12-16].

In this paper, finite difference time-domain (FDTD) method is employed for the analysis of plasmonic nanograting structure/ nanoparticles deposited on glass (silicon dioxide) substrates to enhance the optical absorption in thin-film solar cells. Simulation results show that the plasmonic effect can significantly enhance the trapping of the incident light on thin-film solar cells. Therefore, this light trapping enhancement increases the generation of solar power (energy) and improves the overall performance of the electricity grid. This will provide better grid power supply and long life sustainable power systems.

Smart Grid Systems and Solar Cells

The term Smart Grid is a combination of a number of technologies and is defined in different ways by the policy and regulatory drivers. Some of these definitions are elaborated below.

(i) A Smart Grid is an electricity network that can intelligently integrate the actions of all users including suppliers and consumers connected to it in order to efficiently deliver sustainable, economic and secured electricity supplies [3].

(ii) A smart grid uses digital technology to improve reliability, security, and efficiency of the electric system from large generation through delivery systems to electricity consumers and a growing number of distributed-generation and storage resources [4].

(iii) A smart grid uses sensing, embedded processing and digital communications to enable the electricity grid to be observable

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(able to be measured and visualized), controllable (able to be manipulated and optimized), automated (able to adapt and selfheal), fully integrated (fully interoperable with existing systems and with the capacity to incorporate a diverse set of energy sources) [5].
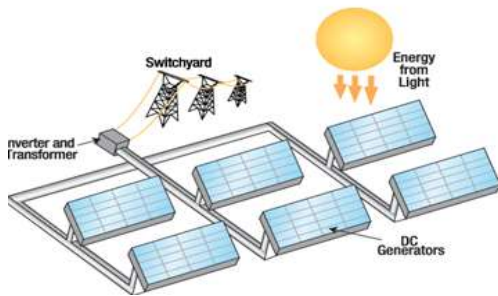
Fig. 1. Proposed smart grid system with integrated solar panels for the generation of solar (renewable) energy from the sun light [17]

Fig. 1 shows a basic schematic diagram for the generation of solar energy using solar panels that are integrated into the electricity grid [17]. The smart grid technology has a growing interest towards the improvement of its efficiency which can be achieved through the addition of high efficient solar panels.

A solar (photovoltaic) cell is a device that converts light directly into electricity through the photovoltaic effect. The term "Solar Cell" is reserved for devices intended specifically to capture the energy from the sunlight, however, the term "Photovoltaic Cell" is used when the light source is not specified. The assemblies of cells are used to make the solar panels, solar modules or photovoltaic arrays. The photovoltaic is the field of technology and research related to the application of solar cells in producing electricity for practical use, such as, industries, offices and household etc. and the energy generated through this way is called solar energy or solar power [9-10, 12-15]. In addition to its simple installation and ease operation, there are several advantages of solar cells over traditional non-renewable energy sources, such as, coal, gas, oil and nuclear. The advantages include: (i) it is totally non-polluting and clean energy source, (ii) there are no moving parts and hence there are no friction losses, (iii) it has long lifetime and (iv) it incurs low maintenance cost. Solar cells (solar panels) can be installed on the roof of any building where the sun light is available during the day time and allowing individual users to generate their own power, quietly and safely.

**Plasmonics for Solar Cells**

In this section, the plasmonics nano-grating and nano-particles structures for high efficiency solar cell are presented. These structures can enhance the overall performance of the electricity grids.

Due to the global demand for green and economic power generation, thin-film solar cells have become very promising choice. The use of resonant properties of metallic nanostructures has opened the new opportunities for significantly enhancing the conversion efficiency of mass-produced solar cells at low cost. To generate electrical energy by a solar cell, photons (light quanta) must be absorbed by the semiconductors and the metal surface nanoparticle has been used to enhance the light-generated current in ultra-thin silicon solar cells [7-8].

Fig. 2 shows the light directly hitting the solar cell (metal nanoparticle) that will excite a surface plasmon resonance on the metal nanoparticle which will re-radiates the light into a trapped waveguide mode in the solar cell substrate [9].
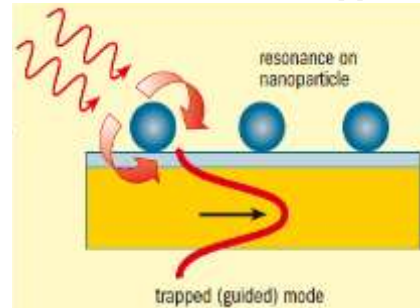
Fig. 2. An illustration of how surface plasmon resonances on metal nanoparticles scatter incident light into guided modes of a thin semiconductor layer [9]

Excitation of metallic structures can lead to oscillation of the conduction electrons, known as surface plasmons. The surface plasmons can improve the absorption and emission of light from thin planar semiconductor layers by coupling the light with the waveguide modes of the semiconductor layer. This provides an alternative way of light-trapping for thin films that would be too thin for conventional light-trapping structures. Enhancing absorption using surface plasmons also avoids the increase in surface electron-hole recombination that occurs with conventional light trapping methods due to the increase in surface area of the semiconductor layer.

Surface plasmons can couple the emitted light out of the waveguide before it is re-absorbed and potentially can increase the conversion efficiency. The plasmon resonance can be broadly tuned across the visible and infrared frequency range. In this way metallic contacts comprising plasmon resonant spectral absorption features can be designed to match the photovoltaic absorber properties. The existing solar cell has an average conversion efficiency of ~20% [6], however with the application of plasmonics technology; the conversion efficiency will be increased the range upto ~50%.
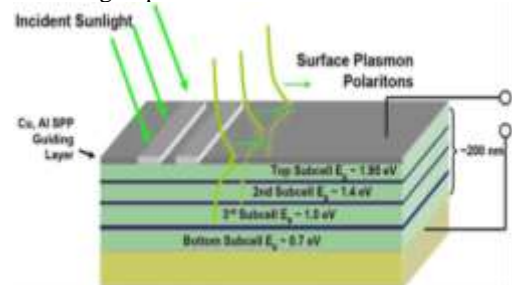
Fig. 3. Schematic diagram of a simple plasmonic nanostructure for a multi-junction solar cell with the conversion efficiency > 45% [18]

Fig. 3 shows the proposed plasmonic nanostructure that will be used in conjunction with the multi-junction active layers comprised of earth-abundant semiconductor absorbers [18]. This plasmonic nanostructure is based on the use of nano-wire grids or gratings instead of the nano-particles that can be engineered and mass-produced through the standard photolithography processes.

Such nano-wire grids/ gratings also have the ability to diminish the solar cell base thickness, yielding to an increase in cell open circuit voltage and enhancing carrier collection for current generation. Based on references [7-9], the plasmonic nanostructure is modeled (as shown in Fig. 4) for high efficiency solar cells to improve the smart grid performance that will deliver a reliable power services.
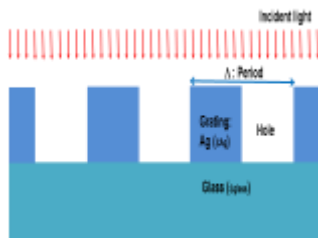
Fig. 4. Schematic diagram of plasmonic nano-grating (Silver: Ag) structures. Here, the Ag nano-gratings on the glass substrate

Fig. 4 shows a schematic diagram for the simulation of plasmonic nano-grating silver (Ag) structure on glass substrates. In this structure, a single period (Λ) contains a grating and a hole (free space) [16]. The incident lights hit directly on top of the plasmonic nano-gratings which are mainly absorbed by the metal gratings but a partial portion of the incident light is reflected. The incident light on metal gratings is converted into propagating surface plasmon polaritons (SPPs) that can absorb the light efficiently in extremely thin (10's~100's of nm's thick) absorber layers. Thin photovoltaic absorbers could revolutionize high efficiency photovoltaic device design by acting as a light concentrator. Plasmonic materials allow full light absorption in extremely thin multi-junction semiconductor structures. The extremely thin absorbers can act as a light concentrator which is essential for the extra ordinary absorption of light in plasmonic nanostructures metal gratings. SPPs are the charge density waves on the surface of materials with free electrons (metals and plasmas) propagating along the interface of conductors and dielectric medium. The oscillating electric fields can excite the SPPs and its field decays exponentially with distance to the surface. The nano apertures in metal surface, periodic holes convert photonics into the SPPs and re-emit photons through metal holes.
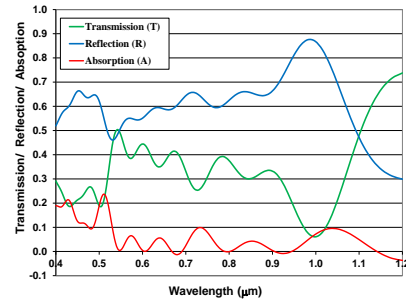
Simulation Results and Discussions

The nanostructure solar cell is simulated using the Opti-FDTD software package developed by Optiwave Inc. [19-20]. For this simulation, a mesh step size is used that satisfies the standard condition of Δx = 10 nm and a time step (span) condition of $\Delta t < 0.1\ \Delta x/c$, where c is the speed of light. The excitation field is modelled as a Gaussian-modulated continuous wave. The incident light wave is considered as a transverse magnetic (TM) polarized (its electric field oscillation direction is along the z-axis, perpendicular to the nano-gratings structures). The anisotropic perfectly matched layer (APML) boundary conditions are applied in both x- and z- directions.

Fig. 5 shows the total electric field density (transmission) plot at a point in the substrate which is the vector summation of the complex electric field along the x-direction (E_x) and z-direction (E_z). The significant amount of light is passed through the holes (free spaces) due to the effect of SPPs which can couple with light and concentrate the energy into a very small place. A custom-designed Matlab algorithm is used to calculate the total electric field intensity distribution. It is clearly shown in Fig. 5 that significant amount of light passing through the region of nano-grating structure which is mainly due to the plasmon-assisted effects that results in propagating SPPs excited by the incident light waves and concentrated (by plasmonic lenses) within the nano-grating region. The light transmission inside the substrate depends on the nano-grating profile as well as its size and shape [19].
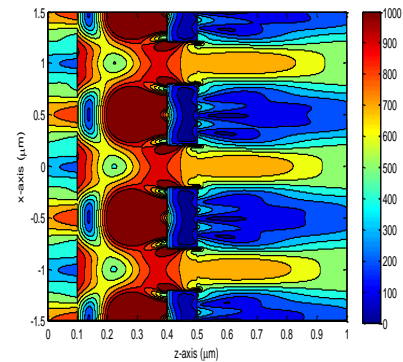

Fig. 5. Total electric field density (transmission) at a point in the glass substrate

Fig. 6. Light transmission, reflection and absorption spectra of silver nanograting structures with a period of 1000 nm (600 nm Ag grating and 400 nm free space or hole) and thickness of 100 nm

Fig. 6 shows the simulation results of the light transmission (T), reflection (R) and absorption (A) spectra of a metal (Ag) grating structure with a period of 1000 nm. In this simulation, a grating length of 600 nm, a hole (free space) length of 400 nm and a thickness of 100 nm have been assumed. The maximum light reflection and minimum light transmission have been observed at the end of the period which is called the plasmonic resonance point. The simulated results are qualitatively agreed with the reported results in [11]. The simulation results are useful for the design and development of high efficiency solar cells to improve the reliability and sustainability of the electricity grids.

The light transmission, reflection and absorption for the nano-particles structures are also simulated as shown in Fig. 7.
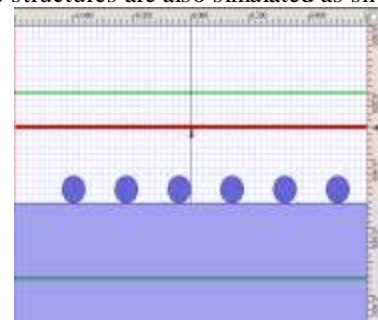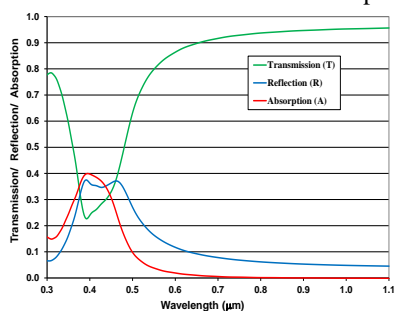

Fig. 7. A simple schematic diagram for the simulation of light transmission, reflection and absorption for silver nanoparticles using the Opti-FDTD software. Here, the silver nanoparticles are on the glass substrate and its diameter is ~ 200 nm

Fig. 7 shows a schematic diagram of sliver (Ag) nanoparticles on top of the glass substrate. For this modeling/ simulation, the diameter of the nanoparticles ~200 nm is used. The FDTD software is used to simulate this nano-structure and the light transmission, reflection and absorption are calculated.

The transmitted light is calculated inside the substrate and reflected light is calculated behind the incident light (red line) by using an observation line.

Fig. 8 shows the simulation results of light transmission, reflection, and absorption versus the wavelength. A notch is observed in the transmission spectra which represents the plasmonic resonance (where minimum transmission, maximum reflection and maximum absorption of light) at wavelength of ~390 nm. This minimum transmission is due to the maximum absorption and reflection at the plasmonic resonance wavelength of the silver nano-particles. Simulation results show that the plasmonic resonance occurs within the visible spectrum range.

Fig. 8. Simulation results of light transmission, reflection and absorption for silver nanoparticles, where a notch is observed about 390 nm, which is the plasmonics resonance of silver nanoparticles

Conclusions

The plasmonic metal nano-grating and nano-particles structures on the glass substrates to enhance the absorption of light are analysed. This concept is used to design the plasmonics based high efficiency solar cells for smart grid application using the FDTD software. Simulation results clearly show that there is a notch in the transmission spectra where minimum transmission, maximum reflection and maximum absorption of light at a certain wavelength and this notch represent the plasmonic resonance wavelength. The minimum transmission is occurred due to the maximum absorption and reflection at the plasmonic resonance wavelength of the silver nano-particles. The proposed plasmonics-based high efficiency solar cell will reduce the energy cost for the consumers and sustain a long life healthy smart grid system. Finally, we conclude that the proposed high efficiency plasmonics-based solar cells will provide improved energy efficiency and reliable smart electricity grids.

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