INP-BASED NANO SOLAR CELLS

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ABSTRACT

Light trapping enhancement is a major research field in photovoltaics. Scarce and expensive resources for semiconductor material drive the research on light management in thin absorber layer. This paper reviews some of the known techniques, from back reflector to nanophotonic technologies such as nanowires or plasmonic-enhanced photovoltaic devices. Light trapping enhancement can reach ~100 fold and experimental demonstrations of device exceeding the ray optics limits have been reported.

Keywords: plasmonics, nanowire, photovoltaics, light management

1 INTRODUCTION

Installed photovoltaic capacity experiences an exponential growth from 0.003 GW in 1995 to 130 GW at the end of 2013 all around the world [1]. This fast development is mainly due to the improvement of solar panels efficiency altogether with a cost decrease making possible to reach the grid parity. The leading photovoltaic technology in terms of photovoltaic market is crystalline silicone (c-Si). Its module price was ~0.85 $/W in 2012 with commercial module efficiency of higher than 20% for Si ~200 µm thick [2]. Even if silicone is the third most abundant material in the Earth crust, material cost represents ~40% of the total cost of a c-Si PV module. An interesting mean of reducing this cost is to reduce the amount of silicone used in the module while keeping the same conversion efficiency. Moreover, c-Si share in the PV market regularly shrinks since 2000 compared to other PV technologies such as CdTe or Cu(In,Ga)Se_2 (thin films technologies) or organic photovoltaics (OPV). Many of these emerging technologies require expensive and/or scarce materials (Te for CdTe, In for Cu(In,Ga)Se_2) leading to the need of raw material saving to drop the costs and avoid material shortage. The carrier collection length and impurity recombination are reduced when the active layer is thinner, which converges to a better conversion efficiency.

A significant effort has been made to find different means to reduce the absorber thickness. This paper aims at reviewing what has been done and how our work falls within this research trend.
Reducing the active layer thickness is not drawback-free and compromises the optical absorption. The proportion of absorbed light on a one way path follows Beer's Law:

$$\frac{I}{I_0} = 1 - \exp(-\alpha . d) \tag{1}$$

Where I/I_0 is the ratio between the absorbed flux and the incident flux, α is the absorption coefficient of the absorber material and d the absorber thickness. From this law we see that to capture 95% of the photons, the thickness needs to be kept higher than $3/\alpha$. As a consequence, enhancing the path length is mandatory to keep a thick optical thickness despite

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a thin physical thickness in order to not compromise the short-circuit current (Jsc) of the solar cell. As described later in this paper, at sub-wavelength scale, absorption enhancement also relies on local permittivity change.

The first part of this paper is dedicated to light path enhancement through a back surface reflector. Although efficient, this approach cannot exceed the classical limit of light concentration and is not conceivable for nanodevices. That is why other light concentration means will be reviewed, from periodic light trapping structures, nanowires to plasmonic-enhanced photovoltaic devices. Finally, Metal-Insulator-Metal (MIM) structures will be studied in more details.

2 BACK SURFACE REFLECTORS AND CLASSICAL LIMIT

The simplest way to increase the path length is to put a reflective layer at the back of the solar cell. If the reflector is specular, the path length will be at least doubled. Additionally, the active layer acts as a waveguide due to the back reflector and front reflection, which ultimately increases the light path length (incident wave coupled to waveguide modes). Even if a metallic layer acts as a back reflector, it provides poor trapping because reflection coefficient needs to be as close as possible to unity. To do so, gratings can be used to create a specular back reflector. A Bragg reflector is a 1D stack of several dielectric layers of alternating materials of different refractive indexes. Interferences occurring inside the Bragg reflector can be either constructive or destructive (according to the wavelength) leading to high transmission or reflection [3]. Being strongly sensitive to the wavelength and the incidence angle, Bragg reflector are not suitable for broad-band reflection but can be used for some thin film solar cell to reflect the narrow spectrum ranged (wavelength close to the bandgap) not absorbed in one way path.

Lambertian reflector can also be used to enhance the light path length inside the absorber material. A reflector is said lambertian if the light is reflected along all directions with the same intensity. First works on lambertian scattering were conducted by Yablonovitch group as well as Goetzberger group [4,5]. They demonstrate than a lambertian reflector of ideal reflection coefficient localized at the bottom of the absorber layer leads to a path length enhancement of $4n^2$, n being the refractive index of the absorber material.

A 40% broad-band photo-current enhancement for a thin-film photovoltaic cell as been reported [6]. It was obtained by modifying the photon density of state by using specifically designed dielectric mirrors. An increase of electric power conversion of a factor 4.3 due to light path enhancement was reported in [7] for an OPV cell. This result, commonly called the classical limit, is valid only if the system can be entirely described by geometrical optics. Reflector needs to be rough (roughness higher than the wavelength) to be lambertian, which cannot be the case for nano solar cells operating in the visible spectrum region. Thus others ways of doing light trapping must be adopted.

3 NANOPHOTONIC LIGHT TRAPPING GRATING AND PHOTONIC CRYSTAL

2D and 3D gratings placed on (or below) the absorber layer have been proposed to perform nanophotonic light trapping. Mokkapati and Catchpole published a good review mainly focusing on these gratings [8]. The idea behind nanophotonic grating of period smaller than the visible wavelength is to create a device in which the incident plan wave can be coupled to more diffraction modes in the absorber layer than in the air. Indeed, the incoming plan wave can be coupled only to the 0^{th} diffraction order in air whereas it can be coupled to numerous propagating diffraction modes inside the absorbing layer (for period lower than the incident light wavelength). Different kind of gratings based on nanowell has also been developed [9] as well as different nanophotonic light harvester [10]. Photonic crystals (PC) provide also a mean of enhancing the light path in a photovoltaic device.

PC can reflect light from any angle provided the wavelength and polarizations remain within the photonic bandgap [11]. The photonic bandgap follows the same physics than the semi-conductor bandgap, Waves must oscillate according to the Bloch's theorem in a periodic medium. When they vary with a period proportionate to the medium period, they concentrate their energy in the low and high refractive index medium, giving rise to a photonic bandgap. Furthermore, diffraction at highly oblique angle, well known for gratings, is also valid for PC, enhancing light trapping. Ref. [12] compares PC light trapping to geometrical optics light trapping. Chutinan and al. [13] performed experimental calculation leading to a theoretical relative increase of 11.15% in the energy conversion in a 2μm thick c-Si with a CP.

Many others examples of light trapping techniques have appeared during the last decade taking advantage of the light property at the nanoscale such as nanowires and plasmonic-based light trapping.

4 NANOWIRE-BASED LIGHT TRAPPING

Nanowire-based devices are becoming more and more attracting since nanofabrication processes become more robust and mastered. It opens the route toward nanodevices such as nanowires exhibiting interesting optical properties. It has been demonstrated by Garnett et al. [14] that ordered array of silicone nanowires increases the path length of incident solar radiation up to 73 times. More recently, Wallentin et al. [15] demonstrated 13.8% efficiency InP nanowires array exceeding ray optics limit.

The light trapping may come from a nanowire array grating effect or light guiding inside each nanowire. The second option is most likely the true reason of path length enhancement according several authors [16-18] due to strong Fabry-Perot resonances inside the nanowire and better performances of aperiodic over periodic nanowires array of the same density. A review article on Si nanowires can be found here [19]. A work on InP nanowire design [20] shows that one can obtain optimal absorption with only 38% active material usage compared to a flat layer benefiting from both near-field enhancement and anti-reflection effect. OPV nanowires have also been reported [21].

5 PLASMONIC-BASED LIGHT TRAPPING

Plasmonics deals with metallic nanostructures exhibiting surface plasmons which ultimately may lead to light concentration inside a thin absorber layer. Several fields in physics can benefit from plasmonics such as optical microscopy, photodetectors, modulators, thermal emitters and photovoltaics. More details can be found in the review of Schuller et al. [22] and Stockman [23]. As described by Atwater and Polman [24] and Pillai et al. [25], mainly two different ways of using plasmonic properties with photovoltaics have been investigated. The first one is light scattering from metal nanoparticles and the second one is the near field effect.

First studies of photovoltaic devices with plasmonic effects were first published in 1995 [26-27], followed by Stuart and Hall [28-29]. They demonstrate an order of magnitude enhancement in the photocurrent for light of wavelength 800 nm by taking advantage of metallic beads-induced light scattering. Latter, Ragip A. Pala et al. [30] gave some rules to design plasmonic resonators and to discriminate light concentration by coupling to waveguide modes and near-field light concentration by localized surface plasmon-resonances. They showed a theoretical 43% short-circuit current enhancement using metallic gratings at the top surface.

The second approach is to take advantage of a near-field enhancement in the absorber layer in the vicinity of metallic nanoparticules. First publications related to this effect are linked with organic photovoltaics in which the diffusion length of the absorber is small (few ten nanometers) compared to inorganic photovoltaics. An interesting review is dedicated to light trapping nanostructures in OPV [31]. Thus, reducing absorber thickness while keeping high optical absorption is of particular interest in this field. Barry P. Rand, et al. [32] showed that more than 10 fold light intensity enhancement on a wide spectral range [500 – 800 nm] was achievable. Rourke et al. [33] showed integrated enhancement of 22% in short circuit current under 1 Sun illumination on an OPV cell with a slot grating structure. Other research teams worked on that field, both on organic or inorganic solar cells [34-35].

6 OPTICAL NANOANTENNA

The structure we decided to study is an InP-based Metal-Insulator-Metal (MIM) structure. This stack was first studied to elaborate optical filter [36-37] but MIM structures have shown interesting optical antenna properties [38]. MIM optical nano-antennas have demonstrated remarkable capabilities in terms of the collection of light in very small volumes. Specifically, they may exhibit, at resonance, almost perfect absorption, independently of angle of incidence, over a very wide angular range (typically between -70 and +70 degrees) and cavity volumes as small as $\lambda^3/1000$ [39]. The resonant character of these antennas, due to the confinement in an optical cavity of coupled plasmonic modes propagating at the metal/dielectric interfaces, means that their spectral width is very small relative to that of the solar spectrum (typically they have a full width at half-maximum of less than a tenth of the resonant wavelength). Asymmetric MIM structures dedicated to the production of photovoltaic cells have been reported in several publications [40-41]. They are based on the simultaneous presence of a plurality of resonances allowing a large part of the solar spectrum to be covered. Although very efficient, the dimensions of these structures are highly constrained due to the conditions that must be met to obtain multi-resonance in the solar spectrum with a given semiconductor.

The electric field enhancement in MIM structures comes from plasmonic near-field enhancement, Fabry-Perot resonances and waveguide excitation mode inside the absorber layer. MIM structures can be used in photovoltaics if the “I” layer is replaced by a semiconductor absorber layer. At optical frequencies, when free electrical charges are generated by doping or illumination, the dielectric constant of the semiconductor doesn’t vary significantly (less than one per thousand). At optical frequencies, a semi-conductive material is a dielectric material which allows to take advantage of MIM optical properties to enhance light absorption. The MIM structure acts as a photovoltaic cell embedded in a nano-antenna. Recently more effort has been done to describe MIM resonators in a more comprehensive way, doing analogy to metamaterials [42]. Consequently the material reduction can be really effective if the geometry is properly designed.

Still one should be careful designing extremely thin MIM structure even if a very efficient electric field confinement is possible, mainly due to plasmonic resonances coupling. It is not compatible with pn or pin junction which jeopardizes electrical performances. In addition, the very nature of plasmonic resonance implies non negligible metal absorption loss. These arguments drive us to consider a thicker resonator ~100 nm to be electrically compatible and to involve other resonance mechanisms leading to less parasitic absorption loss. To counterbalance a thicker thickness, layer structuring is performed to end up with few tens nanometers mean thickness. Fig. 1 displays an example of one of our 2D optimized structure. high electric field confinement inside the active layer requires extremely thin thickness (few tens nanometers) to efficiently couple the two plasmonic resonances at the vicinity of the two metal/dielectric interface

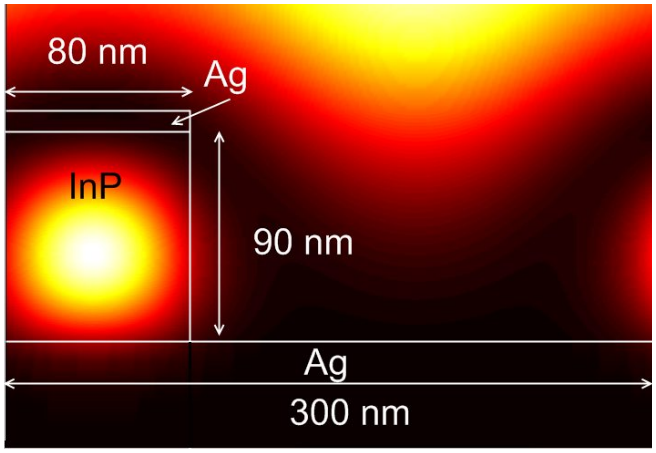

Fig. 1: shows $|E|^2$ field map in TE polarization, at 785 nm wavelength at normal incidence of one optimized lamellar structure.

The MIM structure of Fig. 1 exhibits 77% absorption in the active layer at 785 nm with a 24 nm mean thickness and a global optical efficiency of 40 % for an unpolarized light integrated on all possible incidence angles and on wavelength from 350 nm to InP bandgap.

7 CONCLUSION

In summary, we have shown than numerous ways of enhancing the light path inside a photovoltaic absorber were successfully used. Classical technologies (not exceeding the $4n^2$ concentration limit) may be sufficient in certain cases:

50 fold enhancement for c-Si PV cells. To exceed this limit, different strategies may be used, separately or coupled. Nanowires provide an elegant way to have nearly perfect absorption despite low coverage fraction whereas plasmonic-structures take advantage of near-field or light scattering enhancement. Nevertheless, present light absorber exhibit performances far below perfect black body, knowing that having a perfect absorption on a broad spectrum range, at every incidence angle, for all light polarizations is still a challenge. During many decades, photovoltaics was mainly concerned about electronic properties but this statement becomes less ans less true. Indeed, photovoltaics is a research field which may greatly benefit from efficient light management at the micro/nano scale to reduce cost, scarce and expensive material usage and also to improve charge collection of low minority carrier diffusion length materials.

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