Solar Rectennas - Nanosized Rectenna for Solar Cells

Study Reference Number: 15-2101
Type of activity: Short study (15 k€)

Project Summary

Objective

This project will investigate the use of nanosized rectennas as solar cells in the visible light frequency range for high-efficiency direct conversion of electromagnetic radiation into electricity.

Target university partner competences

Nanotechnology, Nanofabrication, Nanolithography, Materials Characterization, Nano-Imagery, Plasmonics, Antennas

ACT provided competences

Quantum Physics, Metal-Insulator-Metal Tunneling Models, Conductive Tip Atomic Force Microscopy

Keywords

Energy conversion, nano-antenna, rectenna, solar cell, plasmonics

Study Objective

This study aims to investigate direct energy conversion of visible light into electricity using a nano-sized rectenna.

Background and Study Motivation

Current solar cell technology is based in the photovoltaic effect occurring in semiconductor materials. It is well-known that the conversion efficiency of these types of solar cells is theoretically limited as first noted by Shockley and Queisser (S&Q): a crystalline silicon device is limited to a conversion efficiency of 33.7 %. The theoretical limit of an infinite multi-junction cell is 86 %. A nano-rectenna solar cell, combining submicron antennas with ultra-high frequency diode rectification, would theoretically allow direct conversion of electromagnetic radiation into electricity more efficiently, above the S&Q limit. As referred by Moddel and Grover [1], theoretically the efficiency could approach 100 % for monochromatic light.

Rectenna technologies targeting the microwave range have been developed since the early 1960s, have demonstrated power conversion efficiency exceeding 70 % for low-frequency monochromatic radiation [2] and have been demonstrated in space [3]. Despite first proposals for the use of rectennas as solar cells dating back to 1972 [4], only recently demonstrations of this principle have been made in the infrared [5, 6] due to improvements in nanofabrication of both antenna and diode. For instance, Gadalla et al. [7] recently showed plasmonic rectennas at 28.3 THz for energy harvesting purposes. However a proof-of-concept for visible light frequencies (430 – 750 THz) is still missing. Its main challenge is linked to the rectenna's rectifier given that the fastest available diode technology, Schottky barrier diodes, is limited to 5 THz. The Metal-Insulator-Metal (MIM) diode, operating based on quantum tunnelling, is the strongest candidate to extend rectification to hundreds of THz. Quantum tunnelling has been reported to be as fast as 1.8 fs allowing petahertz operation [8], however the working frequency of a MIM diode is always smaller, limited by its RC constant. The RC constant depends on the geometry and materials that compose the MIM rectifier. In particular, as pointed out in [9, 10, 11], a planar MIM is not suitable for infrared and visible frequencies. Other practical geometries comprise MIM travelling-wave diodes [12], geometrical constriction diodes [13] and point-contact diodes (sharp-tip or whisker diodes) [14, 15]. The choice of materials influences critical performance parameters such as the junction asymmetry, the zero bias responsivity and the zero bias resistance, however so far there are not any strong selection criteria concerning material choice. Parameters such as materials workfunction, electro-affinity and interface stability are believed to play a major role [16]. The oxide layer is required to be very thin (~ nm, for measurable tunnelling current) yet high quality and pin-hole free. Simulations by Mayer et al. [17, 18] using a quantum-mechanical transfer matrix approach showed that rectification in the infrared and visible frequencies should be possible using sharp-tip diodes.

A plasmonic sharp-tip geometry such as the one represented in Figure 1 would be particularly advantageous as recognized in [1], since it would allow for a systematic test of materials, opening the way to a comprehensive study of material system design. Such results are expected to be similarly useful in the fields of THz communications and wideband band detection. In particular, as noted in [1], with an optimized material system, such setup can produce the first proof of rectenna operation in the visible light range. This would open the way to the production of highly efficient solar cells using point-contact diodes (making use of large scale production of nanowire point-contact geometric diodes such as in Miskovsky et al. [15]).

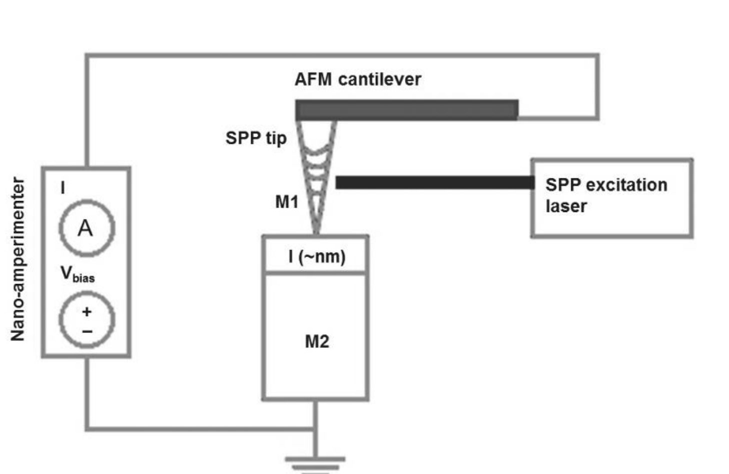

Figure 1: Surface Plasmon Polariton based AFM sharp tip Metal-Insulator-Metal testing structure

The possibility of having more efficient solar cells is of concern for space applications which largely rely in photovoltaic semiconductor technology.

Proposed Methodology

The following gross study logic is proposed, though the proposal of different approaches to achieve the main goals of the study are also welcome:

- Qualitative assessment of prospective combination of materials
- Fabrication of experimental samples and preparation of experimental means
- Experimental set-up mounting
- Investigation of the experimental samples performance: measurements should comprise I-V curve electrical characterization both with and without illumination
- Investigate materials parameters influence on the results

ACT Contribution

This study is addressed to research groups having expertise in the nanofabrication and topological and electrical characterization.

The projected will be conducted in close scientific collaboration with ESA researchers. In particular ESA researchers will contribute to the design of the experiment, discuss sample geometrical concerns, eventually contribute to set-up mounting and to the experimental measurement campaign and analysis.

Bibliography

[1] Moddel, Garret, and Sachit Grover. Rectenna Solar Cells. Springer, 2013.

[2] Brown, William C. "Adapting microwave techniques to help solve future energy problems." 1973 IEEE G-MTT International Microwave Symposium. 1973.

[3] Kaya, Nobuyuki, et al. "Rocket experiment on microwave power transmission with Furoshiki deployment." Acta Astronautica 65.1 (2009): 202-205.

[4] Bailey, Robert Leo. "A proposed new concept for a solar-energy converter." Journal of Engineering for Gas Turbines and Power 94.2 (1972): 73-77.

[5] Abdel-Rahman, M. R., F. J. Gonzalez, and G. D. Boreman. "Antenna-coupled metal-oxide-metal diodes for dual-band detection at 92.5 GHz and 28 THz." Electronics Letters 40.2 (2004): 116-118.

[6] Byrnes, Steven J., Romain Blanchard, and Federico Capasso. "Harvesting renewable energy from Earth’s mid-infrared emissions." Proceedings of the National Academy of Sciences 111.11 (2014): 3927-3932.

[7] Gadalla, M. N., M. Abdel-Rahman, and Atif Shamim. "Design, optimization and fabrication of a 28.3 THz nano-rectenna for infrared detection and rectification." Scientific reports 4 (2014).

[8] Nguyen, H. Q., et al. "Mechanisms of current rectification in an STM tunnel junction and the measurement of an operational tunneling time." Electron Devices, IEEE Transactions on 36.11 (1989): 2671-2678.

[9] Sanchez, A., et al. "The MOM tunneling diode: theoretical estimate of its performance at microwave and infrared frequencies." Journal of Applied Physics 49.10 (1978): 5270-5277.

[10] Sullivan, Thomas E., Young Kuk, and P. H. Cutler. "Proposed planar scanning tunneling microscope diode: application as an infrared and optical detector." Electron Devices, IEEE Transactions on 36.11 (1989): 2659-2664.

[11] Grover, Sachit, and Garret Moddel. "Applicability of metal/insulator/metal (MIM) diodes to solar rectennas." Photovoltaics, IEEE Journal of 1.1 (2011): 78-83.

[12] Hobbs, Philip CD, et al. "Efficient waveguide-integrated tunnel junction detectors at 1.6 μm." Optics express 15.25 (2007): 16376-16389.
[13] Zhu, Zixu, et al. "Graphene geometric diodes for terahertz rectennas." Journal of Physics D: Applied Physics 46.18 (2013): 185101.
[14] Evenson, K. M., M. Inguscio, and D. A. Jennings. "Point contact diode at laser frequencies." Journal of applied physics 57.3 (1985): 956-960.
[15] Miskovsky, Nicholas M., et al. "Nanoscale devices for rectification of high frequency radiation from the infrared through the visible: a new approach." Journal of Nanotechnology 2012 (2012).
[16] Periasamy, Prakash, et al. "Metal–insulator–metal diodes: Role of the insulator layer on the rectification performance." Advanced Materials 25.9 (2013): 1301-1308.
[17] Mayer, A., et al. "Three-dimensional analysis of the geometrical rectifying properties of asymmetric metal-vacuum-metal junctions and extension for energy conversion." Physical Review B 77.8 (2008): 085411.
[18] Mayer, A., et al. "Simulations of infrared and optical rectification by geometrically asymmetric metal–vacuum–metal junctions for applications in energy conversion devices." Nanotechnology 21.14 (2010): 145204.