Fabrication of Infrared Energy Harvester Using Electrically Small Particles

Mohammed R. AlShareef$^{1,2\,*}$, Bo Cui^1 and Omar Ramahi^1
^{1} Department of Electrical and Computer Engineering, University of Waterloo, ON, N2L3G1, Canada
^{2} King Abdulaziz City for Science and Technology, P.O Box 6086, Riyadh 11442, Saudi Arabia
*mohammed.alshareef@uwaterloo.ca

ABSTRACT

This paper presents a novel structure composed of electrically small particles and transmission line to harvest and channel infrared power to a potential load. The proposed harvester is numerically proven able to harvest more than 80% of infrared power at a normal incidence angle. The dispersion effects of the two metallic layers used in the harvester are computed using the Drude model. Fabrication results of the proposed structure before and after adding adhesion layer are discussed.

Keywords: energy harvesting, metamaterials, resonators, nanofabrication

1 INTRODUCTION

The Earth receives more than 100 petawatts (100×10^{15} watts) of solar power that cover different spectrums ranging from infrared to visible waves [1]. More recently, multijunction (MJ) solar cells have proven to convert solar energy with above 40% efficiency [2]. However, the recent solar cell efficiency was achieved under a sunlight concentrator, which means another device along with the photovoltaic module is needed [3]. Furthermore, the multijunction solar cell is usually built by stacking multi layers with different bandgap, resulting in a sophisticated manufacturing and high production cost. Meanwhile to make the photovoltaic technology competitive, its production cost needs to be decreased by a factor of 2-5 compared with fossil fuel.

In our recent work [4], [5], a new mechanism exploiting electrically small particles is proven able to harvest more than 80% of infrared power. This paper shows the fabrication results of this proposed harvester and presents an improved silver adhesion through depositing titanium thin film.

2 DESIGN AND SIMULATION RESULTS

The proposed array harvester is designed using the HFSS [6] simulation tool. The array consists of a silicon substrate coated with silver layers on both sides. On the top side, three mirrored pairs of square split-ring resonators (SRRs) are separated by a microstrip line, while the bottom side represents the ground plane, as shown in Fig. 1. The resulting design parameters of a single SRR are: arm length $L = 40\,\mu m$, arm width $W = 10\,\mu m$ and gap width $g = 10\,\mu m$. The silicon (S_i) wafer has a dielectric constant $\varepsilon_r = 11.9$ and thickness of $h = 50\,\mu m$.

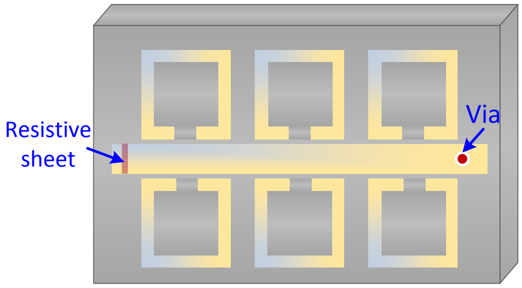
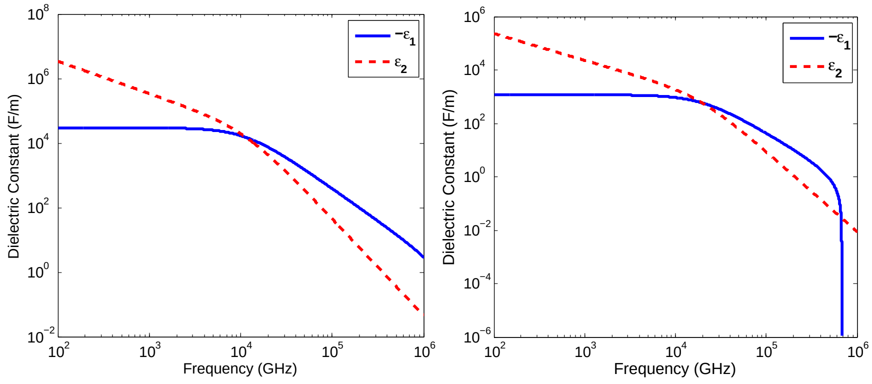


Figure 1: Schematic of the infrared array energy harvester.

The proposed structure is examined numerically by shining a plane wave with different incidence angles. The excited SRRs by the incident plane wave create strong magnetic dipole resonances within their metallic inclusions. Strong electric fields will then be induced at the SRRs gaps due to the displacement currents. Since the SRRs gaps, which have strong electric fields, are in a close proximity to the microstrip line, a strong coupling occurs, resulting in a capability of power channeling.

The power harvesting efficiency of the array is computed by defining a sheet, in square meters, right on the top of the array, and then, the power passing through this sheet is divided by the power absorbed by the resistive load located at the end of the microstrip line. The dispersion effect of the dielectric constant of silver is taken into account by utilizing the Drude model [7], [8]. The real and imaginary dielectric constants of silver are illustrated in Fig. 2a. As depicted in Fig. 3, the structure achieves more than 83% power efficiency at 392 GHz with a normal incident wave.

The silver layer has a weak boundary adhesion to silicon material as will be discussed below, therefore, deposition of another material is necessary to improve robustness. A titanium layer is selected to be deposited underneath the silver layer owing to its low losses at high frequencies and due to its strong adhesion prop-



(a) (b)

Figure 2: The real and imaginary dielectric constants of (a) silver and (b) titanium.

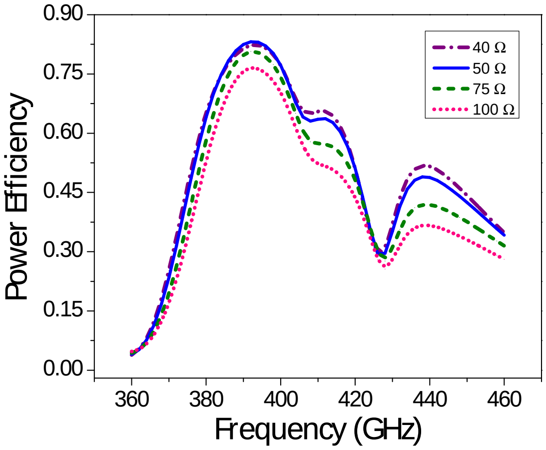


Figure 3: Calculated power efficiency of the array loaded by varying resistive sheet.

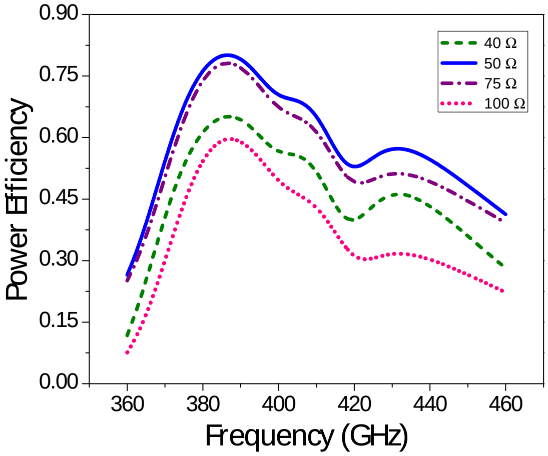


Figure 4: Calculated power efficiency of the array after adding Ti layer and loaded by varying resistive sheet.

erty to silicon substrate. The dispersion effect of the dielectric constant of titanium is also considered by using the Drude model. Fig. 2b presents the dielectric constants of titanium material.

Adding another metallic layer to the structure proposed above will not only change the mechanical properties, but it will also change the resonance response. Hence, the power harvesting efficiency of the array after adding the titanium layer is recalculated in the same manner introduced above. It is found that the new structure yields more than 80% harvesting efficiency at a normal incidence angle and with optimal load of 50 Ω, as shown in Fig. 4. There is also a slight frequency shift of approximately 5 GHz after adding the titanium thin film, which is attributed to the change in the electrical properties of the harvester.

3 FABRICATION RESULTS

The structure is fabricated by first coating a PMMA resist on top of a silicon wafer at 3200 rpm resulting in a relatively thick PMMA film (approximately 600 nm), then the wafer was baked at 180^{o}C on a hotplate for 20 min. Then, the resist was exposed to electron-beam lithography (EBL) at 20 keV with area dose of 200 $\mu C/cm^2$, using Raith 150$^{\mathrm{TWO}}$ EBL system. Afterwards, the exposed resist was developed using MIBK:IPA 1:3 solvent, rinsed in IPA that has lower surface energy than water, resulting in less peeling off. Finally, the sample was dried by Nitrogen spray gun.

A silver layer with a thickness of 200 nm is then deposited onto the resist pattern by electron-beam evaporation. Finally, the PMMA resist is lifted off using PG remover, where the resist is dissolved in a heated beaker at 90^{o}C filled with PG remover, therefore, the metal layer on top of the resist is lifted off. Since the PMMA resist used in this structure is quite thick, the resist was left in the PG remover for three days until the resist was completely dissolved. A schematic of the liftoff process used in this work is illustrated in Fig. 5 and SEM image of the patterned array harvester is depicted in Fig. 6.

However, silver metal is not a good candidate for direct contact with silicon material, since it is only weakly adhesive to silicon. As shown in Fig. 7b, some parts of the proposed structure were undesirably detached and parts of the PMMA resist inside the SRRs remained after the dissolving process. Therefore, we first deposited a thin film (5 nm) of titanium underneath the top silver layer, without breaking the vacuum, to enhance the silver adhesion. The silver thickness was decreased to 195 nm to maintain the total metallic thickness of 200 nm. Fig. 7 illustrates the fabricated sample with and without adding a titanium layer.

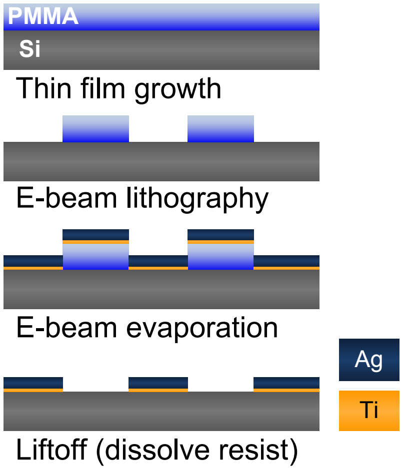


Figure 5: Schematic liftoff process used in this work.

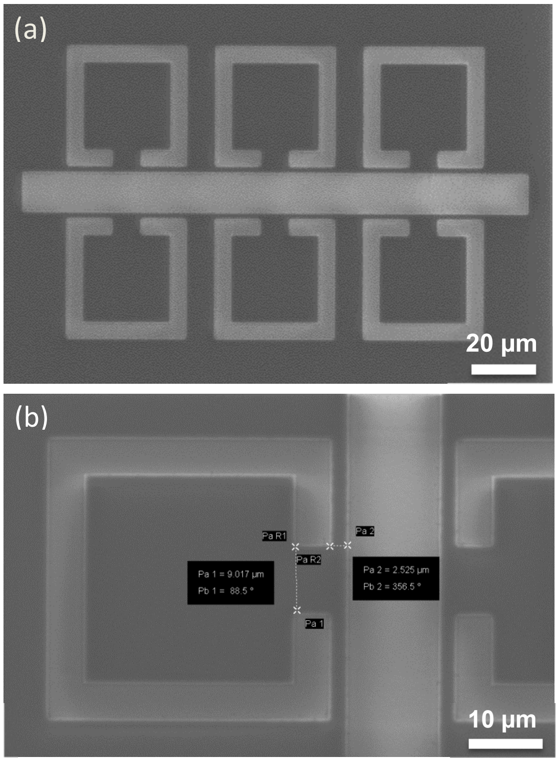


Figure 6: SEM of the structures patterned PMMA resist. (a) The whole array, (b) zoom-in scan of one of the square SRR.

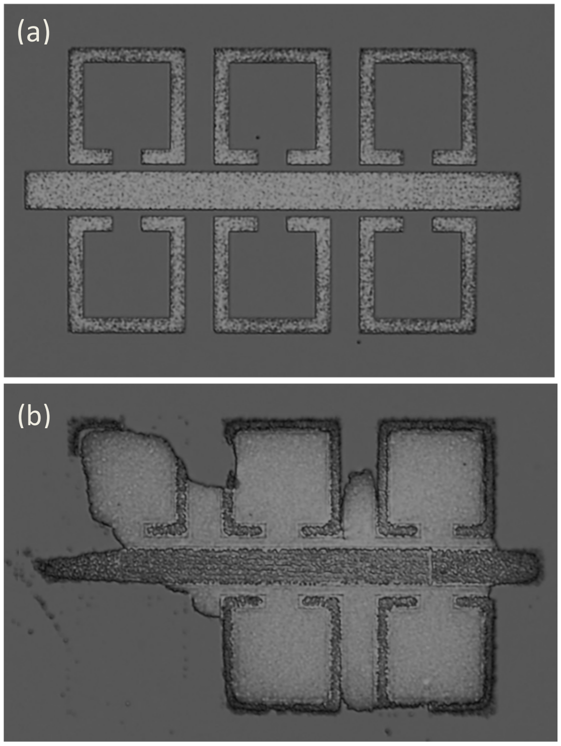


Figure 7: Microscopic images of the fabricated structure. (a) After adding adhesive metal layer, (b) without adding adhesive metal layer.

4 CONCLUSION

We designed an array composed of electrically small resonators to harvest and channel electromagnetic energy in the infrared regime. The numerical results show a high power harvesting efficiency reaching more than 83% and 80% before and after adding Ti thin film, respectively, at normal incidence angle. We also fabricated the proposed harvester using the conventional liftoff processes and enhanced the structure robustness by adding a thin layer of titanium. Future work will validate the theoretical findings presented here through experiments.

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