Power generation from thermal radiation: Photon-assisted tunneling in a metasurface-coupled rectifier

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Abstract

Electrical power generation from a thermal source is demonstrated using a large-area metasurface-coupled tunnel diode rectifier. Transverse electric field confinement in the tunnel gap due to epsilon-near-zero (ENZ) material dispersion from the oxide longitudinal optical phonon mode is shown to enhance the gap field and leads to photon-assisted tunneling. A general model for photo-assisted tunneling is developed and shown to accurately model the short-circuit current in the device. The electrical power generated from the thermal source is measured across a load resistance and the peak power is shown to correspond to the impedance matching condition for a rectifier.

1. Introduction

Energy recovery from a low-grade thermal source requires large-area efficient conversion of infrared radiation into electrical power. Direct rectification of infrared radiation by means of an metasurface-coupled tunnel diode, called a rectenna, has been proposed for energy harvesting applications[1, 2].

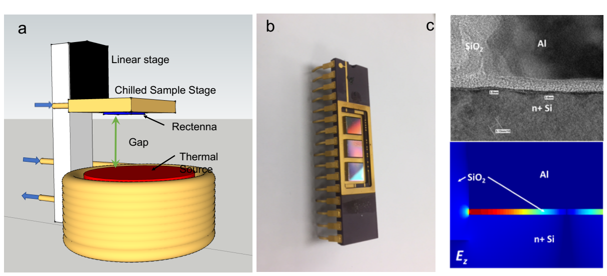

Figure 1: (a) Experimental radiometric power measurement experimental setup (b) Packaged large-area devices for vacuum radiometric testing. (c) SEM image of MOS tunnel diode and EM simulation showing transverse field concentration in the gap. See reference [3].

In this paper, we demonstrate electric power generation from a thermal source in a large-area metasurface rectenna. The rectenna is irradiated with broadband incoherent infrared radiation from a thermal source in a vacuum radiometry setup shown in fig. 1(a)-(b). Previously, we have shown that large photocurrent at zero bias can be observed for metasurface photonic resonances in the region near the LO phonon mode of the oxide[1, 2]. Large transverse electric field enhancement in the tunnel gap leads to large short-circuit photocurrent due to photon-assisted tunneling[3]. (see figure 1 (c)) Photon-assisted tunneling is examined in the transfer matrix Hamiltonian approach and image barrier lowering effects can be observed[3].

2. Results

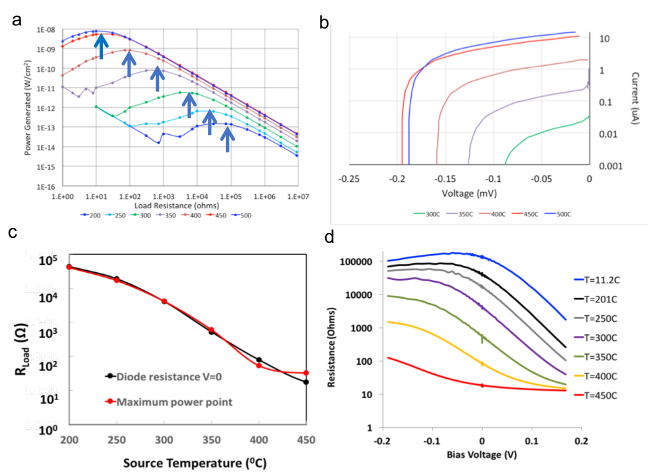

Figure 2: (a) Electrical power generation as a function of the load resistance. Each curve represents a different source temperature. (b) Load diagram in 2nd quadrant. (c) Load resistance at peak power compared to diode resistance at V=0. (d) Diode resistance for various source temperatures.

Power generation from a rectifying antenna requires a load impedance to generate a voltage. Typically, the maximum power point occurs when the load impedance is matched to the coupled-antenna tunnel diode impedance. Power generation from thermal sources occurs due to blackbody emission that depends on the surface temperature and acts like the ac source for our dc power supply. Figure 2(a) shows the measured electrical power over a load resistor as a function of the source temperature. The load line in figure 2(b) shows power generation in the 2nd quadrant indicative of direct rectification The maximum electrical power increases as the temperature is varied from 25C to 500C, peaking at approximately 10nW/cm^2. The load resistance and peak power tracks the tunnel diode resistance at zero bias (see figure 2(c)-(d)) and the tunnel diode resistance decreases with increasing temperature.

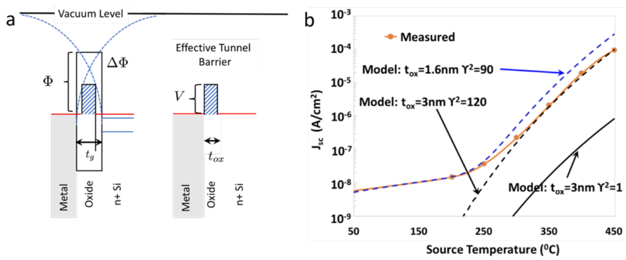

Figure 3: (a) Uniform tunnel barrier model for nMOS tunnel diode including image barrier lowering (b) Comparison of modeled and measured short-circuit photocurrent for various barrier heights, widths and field concentrations. Taken from reference [4]

The measured short-circuit current as a function of the source temperature can be compared to the photon-assisted tunneling model assuming a uniform barrier height for the Al/SiO_2/n+ Si tunnel diode and field enhancement factors estimated from simulation[4]. (see figure 3 (a)-(b)) The incoherent incident transverse electric field is obtained from the blackbody spectral exitance and is dependent on the source temperature. In the model, the photon energy acts as as an effective bias across the device giving rise to large differences between photon emission and photon absorption in the device. The large tunneling current asymmetry is result of the difference in density of states on each side of the barriers.

3. Conclusions

We have demonstrated direct conversion of radiated heat into dc electrical power using a large-area metasurface-coupled tunnel diode. By designing the metasurface photonic resonance near the insulating tunnel barrier material ENZ, we obtain large transverse electric field confinement in the barrier. This enhanced electric field leads to photon-assisted tunneling and results in large measurable photocurrents as a function of the source temperature. A many-body transfer Hamiltonian approach to photon-assisted tunneling has been developed and is in good agreement with experimentally observed short-circuit currents. Nonlinear optical effects due to the ultrafast photon-assisted tunneling current could be a new source of interesting phenomena in the thermal infrared.

Acknowledgement

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