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Design and Performance of Micro-Rectenna Arrays for Thermal Energy Harvesting

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***Abstract*— We report on the design and performance of a micro-rectenna device for harvesting wasted thermal energy. As an individual rectenna exhibits low efficiency and output power, we designed and studied a focal plane array (FPA) on a single semiconductor chip. Our FPA could be used for more general energy-harvesting applications as well as for THz imaging.**

I. INTRODUCTION

Every hot body emits blackbody electromagnetic radiation, where a portion of the energy is concentrated in the mid-infrared and THz band. The idea of harvesting thermal radiation is due to Bailey who first proposed the use rectennas, which consists of the combination of a rectifier and an antenna [1]. Unfortunately this method has not been very well developed because of the technical challenges in manufacturing ultrafast diodes. During the past few years we developed a high speed diode, known as self-switching diode (SSD). Such diodes only require one electron beam lithography step because of its planar architecture. It was recently demonstrated with a high responsivity with a bandwidth up to 1.5 THz at room temperature [2].

By integrating with a broadband antenna with SSD, we designed a new rectenna and experimentally demonstrated its energy harvesting capability for thermal radiation in the far- and mid-infrared region [3]. The energy harvesting theory is based on the Feynman's ratchet and pawl engine, where useful work can be extracted from excess random fluctuations from two reservoirs at different temperatures [4]. Fig 1(a) shows the sketch of the rectenna circuit and thermal source. The incident radiation drives the rectenna out of the thermal equilibrium by increasing the effective temperature of the antenna, rather than its actual temperature, enabling the rectification of excess fluctuations to dc electrical power. Through a HF choke, the dc power is delivered to a resistive load. In our circuit the antenna is not able to consume any dc power so as to improve the conversion efficiency.

II. RESULTS

Our single rectenna unit consists of a wide-band spiral antenna and a SSD [3]. The spiral antenna was a thin Ge/Au layer with a gap of 3 µm. The SSD is fabricated on a two-dimensional electron gas (2DEG) embedded in a GaAs/AlGaAs quantum well 50 nm beneath the surface. The SSD consists of an asymmetric nano-channel, fabricated by etching trenches to insulate the 2DEG, as shown in Fig 1(b).

The experimental measurement was performed using a calibrated high-emissivity blackbody source. The rectenna was placed in front of the blackbody aperture with a field of view of 37° and the temperature was set from 300 °C to 700 °C (approx. 573 K-973 K). The short-circuit current and open-source voltage were measured using a lock-in amplifier with an optically chopped frequency as its reference.

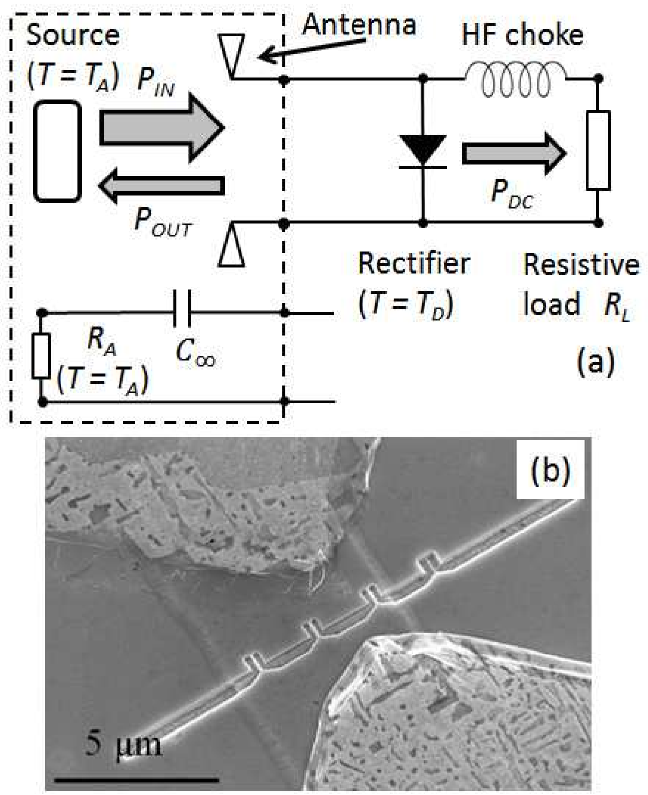

Fig. 1: (a) Schematic of the rectenna as an electronic ratchet. The dashed box shows the equivalent thermal resistor of the antenna illuminated by a source; (b) SEM image of the SSD at the feed point of the spiral antenna.

As shown in Fig 2, the I_{SC} and V_{OC} increase with the temperature considerably and reach their maximum at 6.6 nA and 40 mV at 700 °C (973 K), respectively. Following Feynman's approach, we described the rectification process using the analytical model of the ratchet and pawl engine:

$$I_D = I_0 \left[exp\left(-\frac{\phi - qV_D}{kT_A} \right) - exp\left(\frac{-\phi}{kT_D} \right) \right], \quad (1)$$

where I_D and V_D are the dc current and voltage, respectively, across the rectifier, I_0 is an amplitude scaling factor with the dimension of a current, φ is a characteristic energy which can be identified with the diode built-in energy barrier, q is the elementary charge, and k is the Boltzmann's constant. The antenna and rectifier temperatures are T_A and T_D, respectively. The calculated short-circuit current can be obtained by setting ϕ as 0.94 eV and I_0 as 5.1 mA in the equation and a good agreement to the experimental data confirms the validity of the model, at least in temperature range of our experiments. The V_{OC} shows a poor agreement with the analytical mode because of the SSD reverse current.

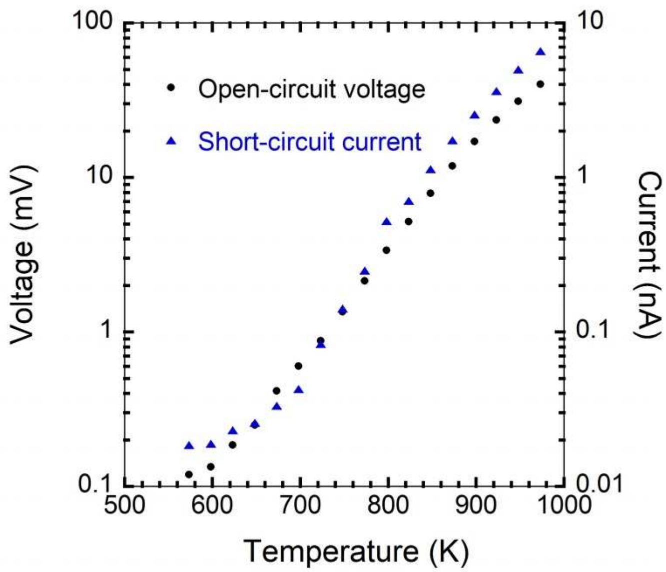

Fig. 2: I_{SC} and V_{OC} as a function of the blackbody temperature.

The thermal source provides an overall input power P_{IN} at the antenna feed point that is equivalent to the thermal noise of a resistor at a temperature T_A. The diode also emits power P_{OUT} at a temperature of T_D, while the diode was kept at room temperature at all time. The equivalent power is obtained according to the Stefan-Boltzmann law without considering the antenna frequency dependency. The overall available power for harvesting is

$$P_{AV} = P_{IN} - P_{OUT} = \frac{\pi^2 k^2}{6h}({T_A}^2 - {T_D}^2), \quad (2)$$

where k is the Boltzmann's constant and h the Planck's constant. The power conversion efficiency was defined as the ratio of the product of the V_{OC} and I_{SC} to the available power. It increased significantly with the temperature because of the reduced resistance of the SSD to improve the power transfer. The maximum efficiency was about 0.02% at 700°C, which is still far lower than the Carnot efficiency. The low efficiency is mainly due to the mismatched impedances of the antenna (~80 Ω) and the nanodiode (~ 6 MΩ), which reflected a considerable amount of energy before transferring to the load. An impedance matched circuit is essential to our device and is currently under development for next-generation rectenna.

We also compared the spiral antenna with a bowtie antenna. The bowtie antenna has a full length of 500 μm and 5 μm gap. The measured V_{OC} and I_{SC} from the bowtie antenna are in the same order magnitude of that from the spiral antenna. We believe that the frequency dependency of antennas is not dominated in our devices because of the impedance mismatch causing a high reflection power transfer loss.

A single rectenna is limited for energy-harvesting applications due to the conversion efficiency and small effective area (or aperture) of the antenna. The fabrication of large rectenna arrays could advance the technology towards practical applications. Recently we have developed a type of focal plane arrays by arranging 11 by 11 individual rectennas on a single chip having a pixel pitch of 400 μm, as shown in Fig 3. The SSDs were fabricated in the center of each antenna. The rectennas were tested individually in the same setup we used above. Due to the variations of nanodiode fabrication, the resistance of rectennas varied, but it was found to be several MΩ on average, which therefore affects the responsivity of the rectenna. In general the higher resistance rectennas produce higher open circuit voltages and better responsivity. The FPA allows studying series and parallel configurations. As each rectenna responses to the THz radiation independently so the FPA can also be used as a THz image sensor, provided a readout circuit is designed in future.

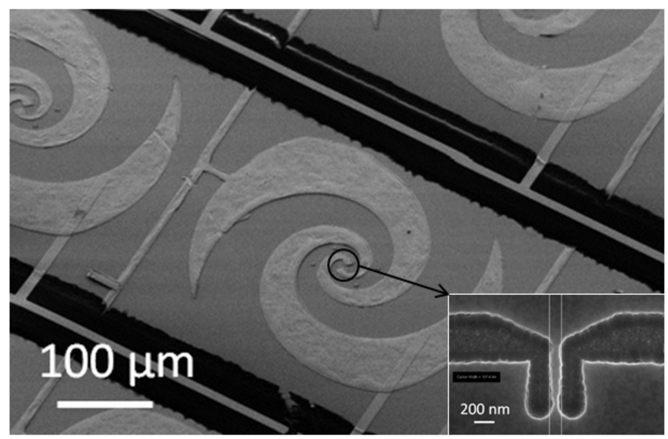

Fig. 3: Scanning electron micrograph of a rectenna element in a large array. The SSD, shown in the inset, is located at the antenna feed point.

III. Summary

We demonstrated a new rectenna to harvest thermal radiation energy in the mid-IR and THz band. The device holds potential for efficient and practical electromagnetic energy harvesting, notably for wasted heat recovery applications in the automotive sector, and for THz imaging and security screening. However, such rectenna relies on epitaxially grown 2DEG material and critical fabrication techniques. We extended our research to develop new types of diodes based on metal-oxide-metal architecture on flexible substrate, because the diodes can be manufactured in a large scale and low cost technique.

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