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InAs thermophotovoltaic cells with high quantum efficiency for waste heat recovery applications below 1000 °C

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ABSTRACT

InAs thermophotovoltaic (TPV) cells with external quantum efficiency at the peak wavelengths reaching 71% at low temperature and 55% at room temperature are reported, which are the highest values to date for InAs. The TPV exhibited 10% power conversion efficiency at 100 K cell temperature. The dark and light current-voltage characteristics were measured at different cell temperatures (100–340 K) in response to heat sources in the range 500–800 °C. The resulting dependences of the output voltage and current as well as the spectral response of the InAs TPV have been extensively characterized for waste heat recovery applications. The performance of these cells is strongly determined by the dark current which increases rapidly with increasing cell temperature originating from bandgap narrowing, which resulted in a reduction of open circuit voltage and output power.

1. Introduction

Large amounts of energy are lost in the form of waste heat in high energy consumption industries such as glass and steel manufacturing. In some processes as much as 20–50% of the waste heat can be lost as radiation. Clearly, a direct and convenient way of converting waste heat into electricity is highly desirable. TPV cells which have very similar operating principles to solar cells can absorb the radiation from hot sources and produce electricity [1]. In addition to energy scavenging, TPVs also have potentials for use in a wide variety of other applications including automotive, mobile power generation and military power supplies and also for space applications where TPVs operating at low temperature can be employed using passive cooling.

Until recently, research work on TPVs has been focused on silicon [2], InGaAs [3], GaSb [4,5] and GaInAsSb alloys lattice matched on GaSb [6,7], most of which have a relatively wider bandgap, making them more suitable for electricity generation from heat sources at temperatures above 1000 °C. Among these, excellent performance has been reported from GaInAsSb TPVs lattice matched on GaSb substrates [6]. Such devices can produce an open circuit voltage (V_{oc}) of ~ 0.3 V, a short circuit current density (J_{sc}) up to 3 A/cm^2, and about 90% internal quantum efficiency (IQE) [8,9]. For higher temperature sources, GaSb based TPVs can achieve ~ 16% power conversion efficiency provided they are illuminated by a high intensity (tungsten) light source [10]. However, for lower temperature (< 1000 °C) heat sources, narrow bandgap semiconductors can potentially result in TPVs with higher conversion efficiency [11,12], mainly because more photons emitted from the blackbody source can be harvested by the low bandgap material. InAs TPV cells (0.35 eV bandgap) appear to be very promising for waste heat recovery. However, until now, much less investigation has been carried out on InAs based TPVs compared with GaInAsSb and GaSb devices. V_{oc} of ~ 0.06 V and J_{sc} of ~ 0.9 A/cm^2 have been obtained from InAs TPV cells illuminated by a 950 °C thermal source [13]. But relatively little information has been reported on the operating characteristics and potential of InAs TPVs. In this work, we report in detail on the characteristics of a TPV cell based on a high quality InAs p-i-n diode grown by metal-organic chemical vapor deposition (MOCVD) for the purpose of waste heat recovery and energy scavenging applications. We report on the electrical and spectral properties for the cell held at different temperatures (100–340 K) when illuminated by low temperature thermal sources (500–1000 °C). We obtained high external quantum efficiency (EQE), short circuit current and approximately 3.6% power conversion efficiency using a 950 °C thermal source.

2. Experiments

The InAs p-i-n TPV devices studied in this work were grown by

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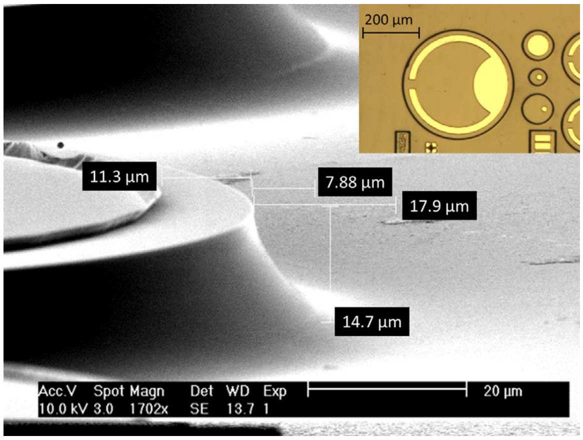

Fig. 1. SEM image showing the etched side wall of the InAs TPV. The inset shows the plan view optical microscopic image of the device.

MOCVD on an n-type InAs (100) substrate. The structure comprised of a 2 µm n+ layer ($1 \times 10^{18}\ cm^{-3}$) followed by an 10 µm intrinsic region and then a 2 µm p + layer ($1 \times 10^{18}\ cm^{-3}$). Ti/Au metal with thickness of 20/200 nm was deposited to form the top and bottom ohmic contacts. The top contact was in a horseshoe shape covering 20% of the surface area as shown in the inset of Fig. 1, which was opaque for the incident radiation. The TPV cells were fabricated by using phosphoric acid and hydrogen peroxide based wet chemical etchant, followed by a finishing etch in sulphuric acid and hydrogen peroxide based solution, to define mesa diodes with diameter of 400 µm. A scanning electron microscopic (SEM) image was taken on the etched device, as shown in Fig. 1. The deep wet etching resulted in the extension of the side walls by about 8 µm, making the actual diameter to be around 416 µm. The finished devices were mounted on TO- headers for characterization.

The current-voltage (I-V) characteristics were measured using a Keithley 2400 source meter. Flash exposure tests were carried out by mounting the cells 10 cm in front of a variable temperature (500–800 °C) blackbody thermal source with an aperture of 25 mm, without any focusing optics. The TPV device was loaded into a liquid nitrogen cooled continuous flow cryostat to measure the I-V characteristics and spectral response at different cell temperatures (T_c). The corresponding spectral response was measured using the same black body source, with a 0.3 m grating monochromator (blazed at 3.5 µm) and lock-in amplifier with a chopper frequency of 65 Hz. The EQE curves were obtained by dividing the spectral responses with the spectrum of the thermal source, which was measured by using a pyroelectric infrared detector. The EQE value of the cell at 300 K 1.55 µm was measured outside of the cryostat by using a 1.55 µm, 1 mW fiber pigtailed laser. The values of the EQE curves were then scaled based on this measured EQE.

3. Results and discussion

The capacitance-voltage (C-V) measurements reported previously revealed a very low background n-doping level of $6 \times 10^{14}/cm^3$ in the intrinsic InAs region [14], which indicated that in the p-i-n structure the depletion region occupied the entire i-region. The top p+ layer can work as the emitter region, and the intrinsically n type undoped region can serve as the base for the InAs TPV. The I-V curves of the InAs cell under 500–800 °C thermal source radiations at cell temperatures T_c = 300 K and 100 K are plotted in Fig. 2(a) and (b). The measurements were carried out when the InAs cell was mounted in the cryostat with a CaF_2 window in front. The power density from the thermal radiation arriving on the cell was measured using a calibrated power meter to increase from 76 mW/cm^2 at 500 °C to 318 mW/cm^2 at 800 °C. As shown in Fig. 2(a), when the InAs TPV cell was kept at 300 K, the I-V curves remained almost linear regardless of the source temperature, corresponding to a fill factor (FF) of 25%. As the source temperature was increased from 500 °C to 800 °C, the short circuit current, I_{sc} increased from 0.04 mA (0.03 A/cm^2) to 0.29 mA (0.23 A/cm^2), almost proportional to the increase in the number of photons from the black body source above the InAs bandgap energy (~ 0.35 eV). The V_{oc} also increased from 5.5mV to 17.4 mV. In contrast, when the cell temperature, T_c was cooled to 100 K, (Fig. 2(b)) the FF substantially improved to 68.5% with the source at 500 °C and reached 70.2% with the source at 800 °C. Although the I_{sc} was reduced by about 31% due to the increase in the bandgap of InAs at 100 K (~ 0.41 eV), the V_{oc} significantly improved to 252 mV with the source at 800 °C - more than 14 times larger than at T_c = 300 K. It is also worth noting that the V_{oc} showed much less reduction when lowering the source temperature at T_c = 100 K. With the 500 °C source, the V_{oc} still reached 208 mV, which was only an 18% reduction compared with the 800 °C source. The calculated power efficiency was 0.071% with the 500 °C source and 0.35% with the 800 °C source when the InAs TPV was at room temperature. However, both values greatly increased to 4.4% and 10% respectively at T_c = 100 K, which was predominantly due to the improvement in V_{oc}. These high power conversion efficiencies at low T_c can possibly make the InAs based TPVs useful in deep space applications, where other sources of energy are not available. Note that the incident power in these experiments is quite low (76 mW/cm^2 at 500 °C and 318 mW/cm^2 at 800 °C) since the TPV cell was inside the cryostat, and that the power conversion efficiency is strongly dependent on both the incident power density and the blackbody emitter temperature. When concentrating the 800 °C radiation to about 4 W/cm^2 at room temperature, the TPV efficiency increased to 1.3%, largely due to the 3 times increase in V_{oc}. Using a 950 °C blackbody source with 720 mW/cm^2 power density as in our previous work, this InAs TPV achieved J_{sc} = 1.32 A/cm^2 at 300 K T_c, which is about 47% higher than the LPE grown InAs TPV with an InAsSbP window layer [13]. The power efficiency was estimated around 3.6%, which is also a little higher than our previously reported value.

The spectral responses of the InAs TPV at these two cell temperatures were shown in Fig. 2(c) and (d). In each case, the shape of the response showed very slight changes by varying source temperature. Only the intensity was increased with higher source temperatures due to more photons above the bandgap energy being captured. The small fluctuations in the spectra in the 1.6–1.8 µm and 2.5–2.8 µm regions were caused by the water absorption in the atmosphere. The spectra in Fig. 2(d) all showed a clear cut-off once the wavelength was above 3.0 µm, indicating that very little absorption occurred below the InAs bandgap when the TPV cell was at 100 K. In contrast, at T_c = 300 K in Fig. 2(c), much broader tails can be observed in all the spectra between 3.5 and 4.0 µm, which can be attributed to the absorption by thermally activated near band edge states. In addition, by comparing these two plots, it is clear that at 300 K the InAs TPV cell exhibited a broader spectral response, while at 100 K the curves became narrower and clear peaks can be observed near the InAs bandgap.

The dark current density-voltage (J-V) curves of the InAs TPV were measured when the TPV cell temperature, T_c was adjusted from 100 K up to 340 K, as shown in Fig. 3(a). The estimated ideality factor n remained at around 1.1 in the measured temperature range. The dark leakage current density J_0 greatly increased by about 4 orders of magnitude when T_c was raised from 100 K to 340 K. We found that the dark current did not drop significantly at temperatures below 100 K. Using an additional metal cap made of 0.2 mm thick nickel which can block all the possible infrared light from the environment, the dark current drops substantially (by at least 2 orders of magnitude), indicating that the device is collecting the 300 K radiation from the optical window of cryostat. Hence, the dark current at 100 K is believed to be largely contributed by the 300 K radiation.

The shunt resistance R_0 of the InAs TPV at different temperatures was estimated from these dark J-V curves near zero bias. The relation