Low Bandgap Mid-infrared Thermophotovoltaic Arrays based on InAs

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We demonstrate the first low bandgap thermophotovoltaic (TPV) arrays capable of operating with heat sources at temperatures as low as 345 °C, which is the lowest ever reported. The individual array elements are based on narrow band gap InAs/$InAs_{0.61}Sb_{0.13}P_{0.26}$ photodiode structures. External power conversion efficiency was measured to be ~3% from a single element at room temperature, using a black body at 950 °C. Both 25-element and 65-element arrays were fabricated and exhibited a TPV response at different source temperatures in the range 345-950 °C suitable for electricity generation from waste heat and other applications.

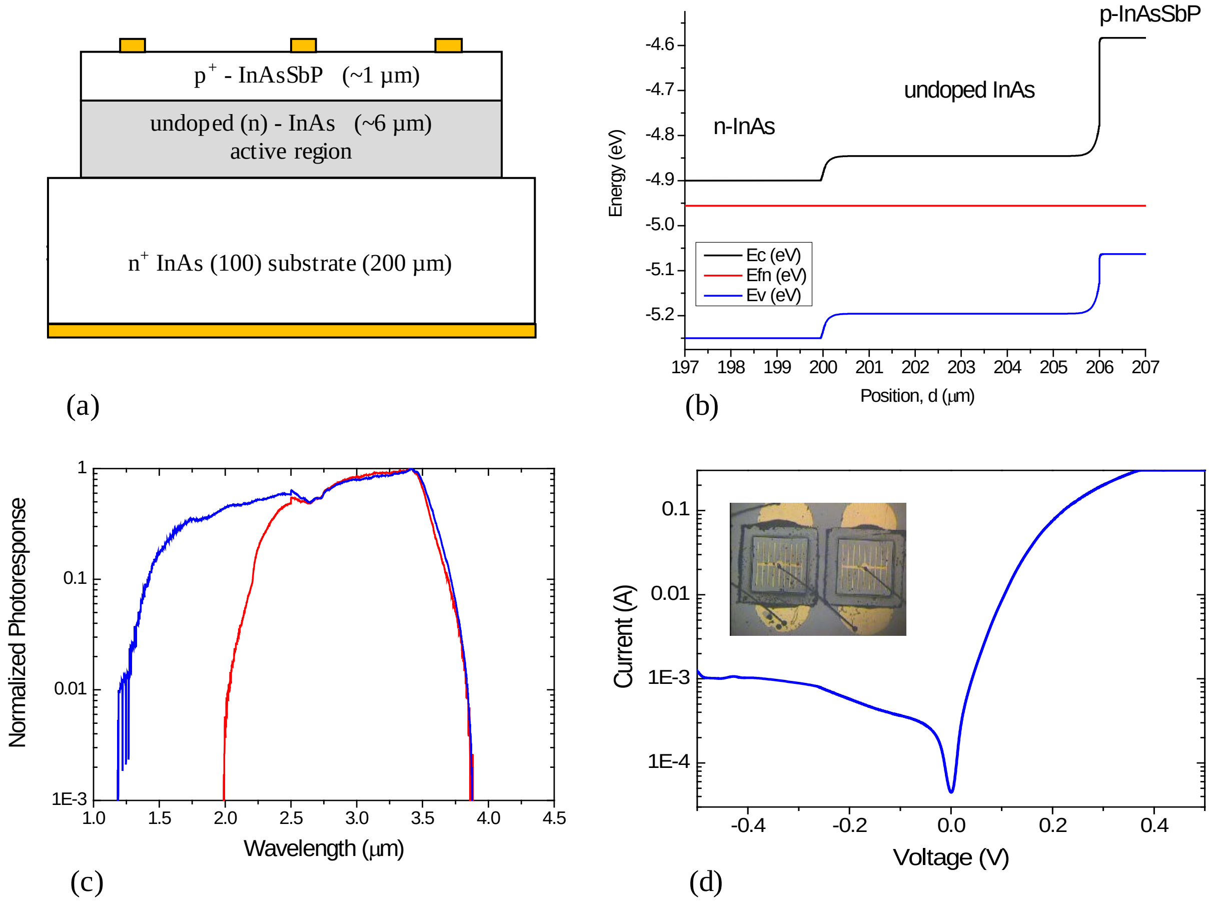
Introduction

There is continuing interest in thermophotovoltaic (TPV) devices because they can provide an attractive method for the direct conversion of heat into electricity in a wide variety of applications, and in particular for industrial waste heat recovery and silent or remote power generation. The optimum TPV cell bandgap depends on the emitter blackbody temperature, and following the thermodynamic detailed balance model,[1] in the ideal case where radiative recombination is dominant, the maximum TPV cell efficiency is ~ 35% for source temperatures between 1200 - 2500 K, such that the optimum bandgap falls in the range 0.2 – 0.5 eV.[2] To date previous work has concentrated on TPV devices matched to high temperature sources using semiconductors with larger bandgaps such as silicon (E_g =1.1 eV), InGaAs [3] on InP (typically E_g = 0.5-0.73 eV, but which is limited by lattice mismatch to the higher bandgaps), or InGaAsSb on GaSb (constrained to E_g = 0.5 eV by a miscibility gap). There have been some studies of the development and characterization of InAs based diodes for lower temperature TPV applications, but, these reports concern mainly epitaxial growth and characterisation of individual elements[4,5]. Meanwhile, although there are currently active investigations into quantum cascade based or multiple-junction TPVs, there are still no TPV arrays capable of electricity generation using thermal source temperatures below 1000 °C [6,7]. In this work we have developed an approach using InAs with a bandgap of 0.32 eV (300 K) and demonstrate prototype InAs-based TPV arrays. These devices have a lower bandgap than conventional GaSb or InGaAs cells and are well-matched to cooler thermal sources at temperatures ~500 °C.

Experimental Procedures

The TPV cell design implemented here is shown in figure 1(a) and comprised a p-type quaternary alloy layer of InAsSbP with bandgap (~0.5 eV) as a window to allow light into the active region and reduce surface recombination of photo-generated carriers. The InAs undoped active region was ~6 μm in thickness to provide effective absorption. The epitaxial layers of InAs and quaternary InAsSbP were grown lattice-matched onto a p-type (100) InAs substrate by conventional liquid phase epitaxy (LPE) using a horizontal sliding boat technique. Growth was implemented from In-rich melts at temperatures within the interval of 570–580 ˚C, using a supercooling (ΔT) ~3˚C based on our previous work[8]. The InAs within the active region was unintentionally doped and was purified during growth using a rare-earth gettering technique to remove residual impurities[9]. The alloy composition of the lattice-matched quaternary alloy as determined by energy dispersive x-ray analysis was found to be $InAs_{0.61}Sb_{0.13}P_{0.26}$. The resulting layers were also characterised using photoluminescence spectroscopy in the temperature range 4–300 K, which was excited using an Ar^+ ion laser (514 nm) which produced an excitation density of 20 W cm^{-2} at the sample surface. The InAs bandgap determined using PL spectroscopy was found to be in agreement with spectral photo-response measurements. Hall Effect measurements using the Van der Pauw method were used to determine the residual carrier concentration which was ~$1x10^{16}$ cm^{-3}. The TPV cells which comprised the array were fabricated by standard ultraviolet photolithography and wet chemical etching techniques. Ti/Au ohmic contacts were realized by thermal evaporation. The mesa (active) area of the individual cells was designed as 1 mm ×1 mm, with a nine (or eleven) finger electrode pattern. No anti-reflection coating or passivation of the cells was used.

For the individual cells the spectral response was measured using a grating monochromator (blazed at 3.5 µm) and lock-in amplifier using a chopper frequency of 180 Hz and a calibrated blackbody at a temperature of 1200 K. The results were corrected and normalised using a pyroelectric (PZT) detector with a flat response. For efficiency measurements, a variable temperature blackbody 300-1200 ^{o}C with an aperture of 25 mm was used as the thermal source. The optical (thermal) power incident on the surface of the TPV cell was measured using a 10 mm-diameter large-area thermopile; (Melles Griot 13 PEM 001/J power meter), constructed from a high-density graphite disc having a uniformity of 81% over the central 8 mm and a dynamic range from 2 µW to 2 W. In all cases the TPV cells were positioned normal to the incident radiation and a correction was made to account for the field of view of the thermopile. The lower temperature efficiency was also measured with the TPV cell(s) at room temperature using a calibrated black body source at 500 ^{o}C (Landcal P550P) with a 65 mm diameter aperture.

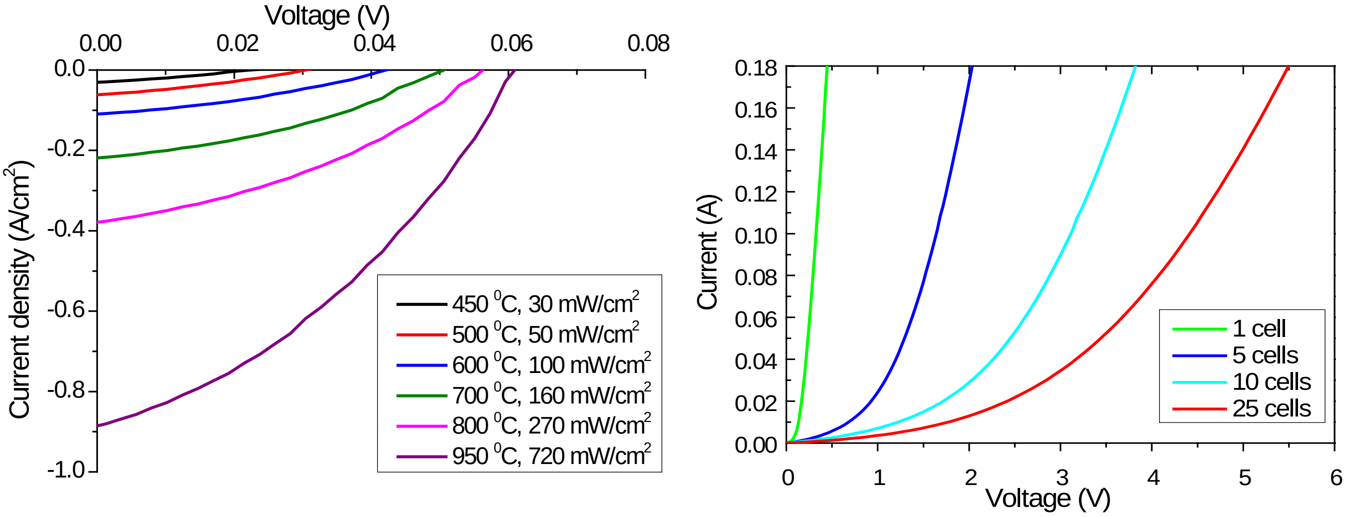


(a) (b) (c) (d)

Figure 1. (a) The structure of the InAs-based TPV cell with lattice-matched $InAs_{0.61}Sb_{0.13}P_{0.26}$ quaternary window layer; (b) the simulated energy band structure of the cell at zero bias; (c) the spectral response of the TPV cell with p-InAsSbP window (blue curve), compared with that of an InAs homojunction cell without a window (red curve). The bandgap determined from the cut-off wavelength is 0.32 eV; (d) the current-voltage (I-V) characteristic of the TPV cell in the dark: the inset shows two individual cells connected in series.

Results

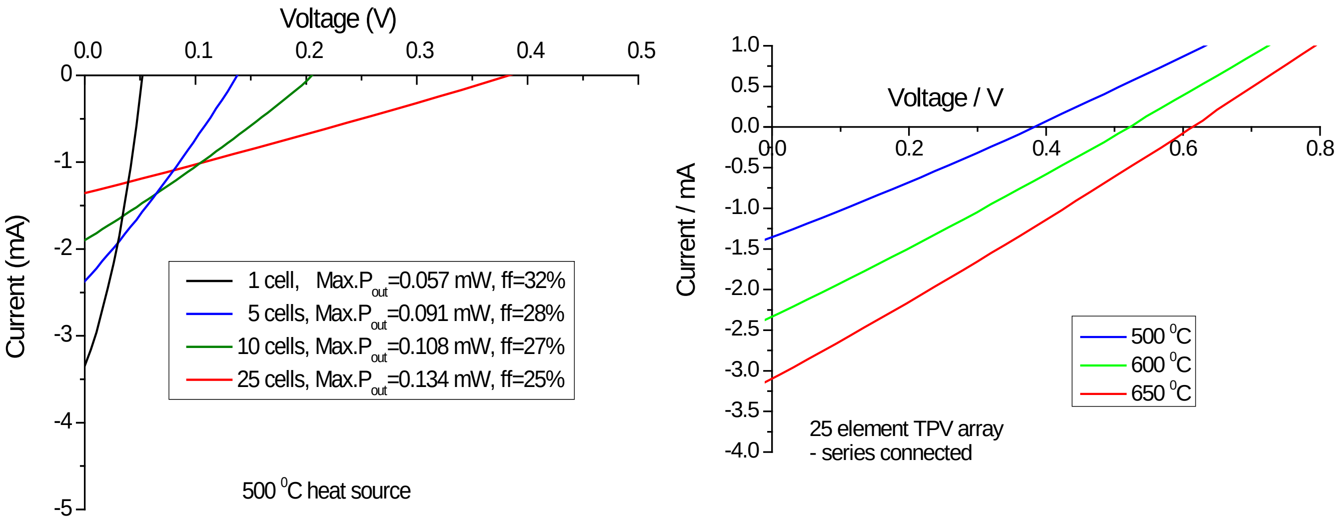
Figure 1(b) shows the simulated energy band diagram for the structure at zero bias obtained using SimWindows[10]. The p-InAsSbP window enables long wavelength photons to be absorbed within the undoped InAs active region, but also contributes to the TPV response. As shown in figure 1(c) the long wavelength cut-off is determined by the InAs, whereas the InAsSbP effectively extends the short wavelength photoresponse which is limited by the non-radiative recombination of photogenerated carriers at the device surface. The current-voltage (I-V) characteristic of a single element is shown in figure 1(d) from which the ideality factor was obtained as 1.4 with a shunt resistance of 217Ω and a series resistance of 0.75Ω at 300 K.



(a) (b)

Figure 2. (a) The TPV response (J_{sc} vs V) of a single array element obtained using a black body at different temperatures in the range 450 ^{o}C - 950 ^{o}C. The corresponding incident power density at each temperature is given in the legend; (b) the dark I-V curves of different numbers of array elements connected in series connection at room temperature.

The TPV response of a single array element is shown in figure 2 (a) for blackbody source temperatures in the range 450 ^{0}C- 950 ^{0}C. Due to the low bandgap of the InAs (0.32 eV) as determined from the spectral response in Fig. 1(c)), the cell generates power at low source temperatures within the range suitable for waste heat recovery applications. The maximum open circuit voltage (V_{oc}) and short circuit current density (J_{sc}) were measured as 0.06 V and 0.89 Acm^{-2} for a blackbody temperature of 950 ^{o}C and an incident power density of 720 mWcm^{-2}. The fill factor was obtained as 37% with a corresponding efficiency of 3% (after correcting for obscuration by the metal electrode). The individual InAs TPV cells were assembled and tested in a 25-element array, where the individual elements were separately mounted onto an AlN insulator to provide electrical isolation and wire-bonded in series. (Monolithic arrays on InAs substrates could not be fabricated because semi-insulating substrates are not available). The dark I-V curves obtained from 5, 10 and 25 cells in series connection are shown in figure 2(b), where the series resistance increased from 0.5 Ω (1 cell) to 13 Ω (25 cells). The dark I-V characteristic of the 25-element array in Fig. 2(b) shows that the array as a whole maintains a diode behaviour at 300 K.

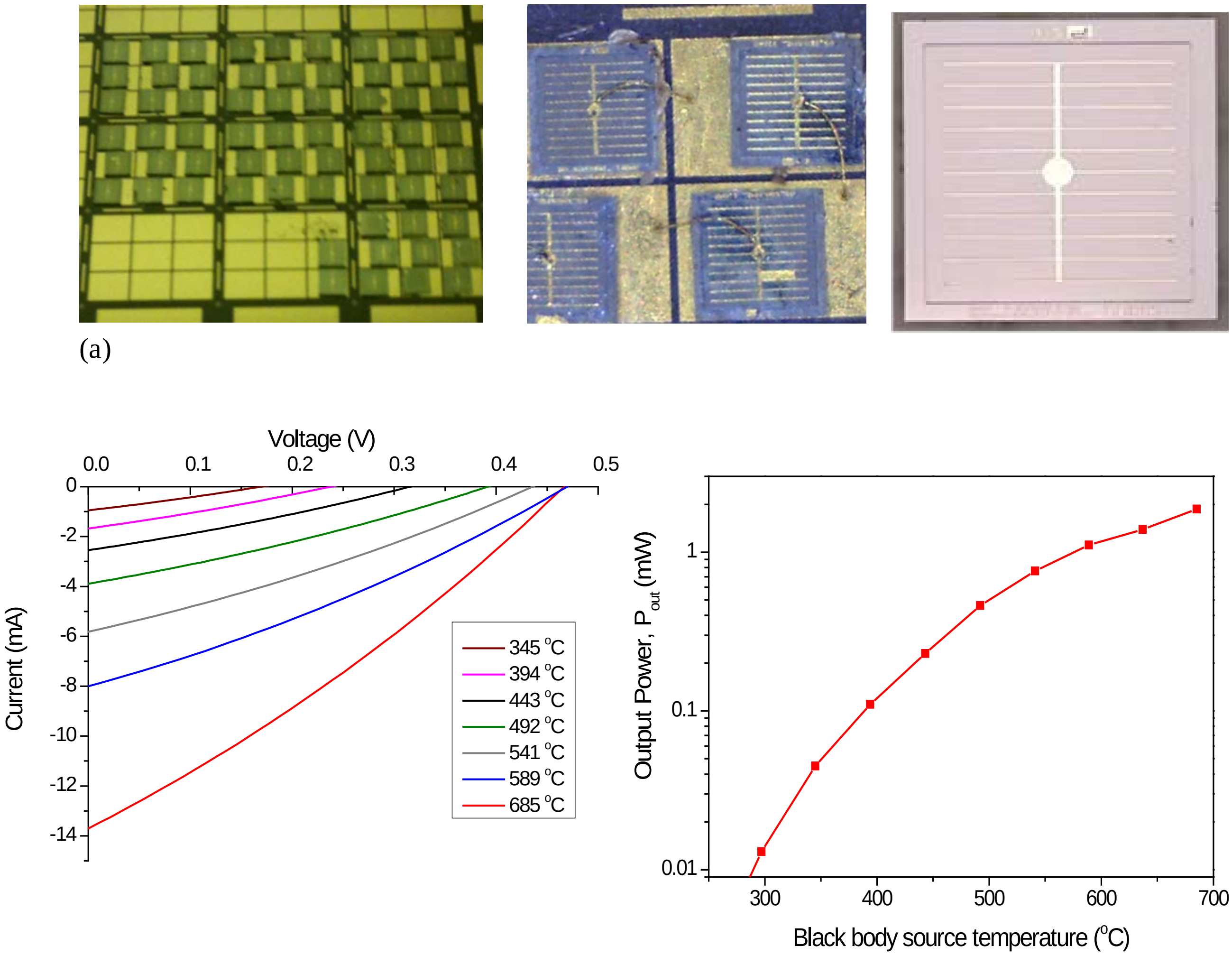


(a) (b)

Figure 3, The TPV response of the InAs based 25-element array; (a) The current-voltage (I-V) curves measured from 1,5,10 and 25 cells connected in series, illuminated using a 500 °C black body source (800 mWcm^{-2}). The corresponding output power and fill factor of each combination are given in the legend. (b) The resulting current-voltage (I-V) curves measured from the 25-element array illuminated using a black body at different temperatures.

The I-V curves for different numbers of elements in the array measured using 500 ^{0}C black body illumination with relatively low incident intensity (800 mWcm^{-2}) are shown in figure 3(a). As the number of cells was increased the open circuit voltage increased from 0.05 V to 0.38 V and the total output power increased up to 0.134 mW, (which equates to 0.35 mWcm $^{-2}$). However, the fill factor was reduced from 32% to 25% as the number of cells increased, due mainly to the increase in series resistance and the corresponding reduction in the short circuit current which decreased from 3.4 mA to 1.3 mA. This highlights the importance of minimising the series resistance for such TPV arrays and further development of the mask design and processing is needed to improve performance. Figure 3(b) shows the behaviour of the 25-element array in response to a black body source at different temperatures. The short circuit current and the open circuit voltage both increased with increasing source temperature as expected due to the increased total radiant output power.

We also fabricated a 65-element array as shown in Fig. 4. The individual elements were fabricated in the same manner as the 25-element array but here the individual cells were provided with 11 finger electrodes instead of nine.



(a)

(b)

(c)

Figure 4. (a) Left - the general arrangement of the 65-element array; Centre - some of the individual elements showing the series interconnection and the 11 finger top contact electrode; Right- an individual array element showing the detail of the contact electrode and etched mesa. (b) The TPV response of the 65-element array to a black body source at different temperatures given in the legend, (c) the corresponding output power obtained from the array in response to the black body source at different temperatures.

The current-voltage response of the 65-element array at room temperature is shown in figure 4(b) when exposed to a black body at different temperatures. The array shows a measurable TPV response at a source temperature as low as 345 ^{o}C, which to our knowledge is the lowest reported to date. Both the short circuit current and open circuit voltage increased with increasing source temperature. The evolution of the output power is shown in figure 4(c) where we obtained a maximum of 1.9 mW at 685 ^{o}C compared to 0.013 mW at 297 ^{o}C. Higher output power can be obtained by increasing the incident heat flux but this warms up the TPV elements so that active forced air or water-cooling needs to be implemented in practice.

Conclusions

We have developed narrow band gap $InAs/InAs_{0.61}Sb_{0.13}P_{0.26}$ heterojunction photodiode structures for thermophotovoltaic (TPV) electricity generation from (waste) heat sources at temperatures below 1000 ^{o}C. For a single element the maximum open circuit voltage (V_{oc}) and short circuit current density (J_{sc}) were obtained as 0.06 V and 0.89 Acm^{-2} for a blackbody temperature of 950 ^{o}C and an incident power density of 720 mWcm^{-2}. The fill factor obtained was 37% with a corresponding efficiency of 3% with the cell at room temperature. These InAs-based TPV cells were fabricated into prototype series-connected 25-element and 65-element TPV arrays. The open circuit voltage increased from 0.05 V for one element up to 0.38 V for 25 elements and the total output power increased up to 0.134 mW, using a 500 °C source. However, the fill factor reduced from 32% to 25% as the number of elements increased, due mainly to the increase in series resistance and the corresponding reduction in the short circuit current. Using a series interconnection of 65 single elements we demonstrated the first low bandgap InAs TPV array capable of operating with heat sources at temperatures as low as 345 °C which is the lowest reported to date. Further development is needed before practical implementation, including optimisation of the top contact electrode, reduction of series interconnection resistance and provision of anti-reflection coating. However, we have shown that InAs low bandgap TPV arrays can operate with cooler heat sources at temperatures in the range 345– 950 °C suitable for electricity generation from waste heat and other applications.

Acknowledgements

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