GeSn Mid-Infrared Thermophotovoltaic Cells for Power Beaming and Heat Conversion

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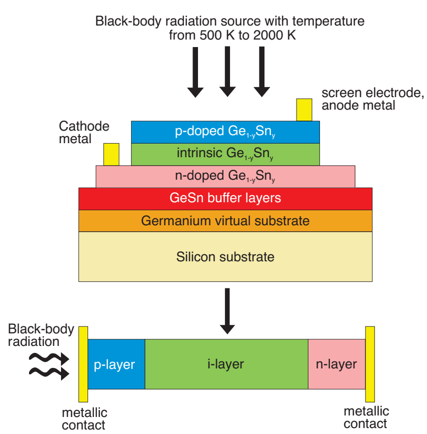
Compound semiconductors have been the predominant building blocks for the current mid- infrared thermophotovoltaic (TPV) devices relevant to sub-2000 K heat conversion and power beaming. However, the high cost associated with these technologies limits their broad adoption. Herein, to alleviate this challenge we introduce an all-group IV mid-infrared cell consisting of GeSn alloy directly on a silicon wafer. This emerging class of semiconductors provides strain and composition as degrees of freedom to control the bandgap energy thus covering the entire mid-infrared range. The proposed TPV device is composed of a fully relaxed $Ge_{0.83}Sn_{0.17}$ p-i-n homojunction corresponding to a bandgap energy of 0.29 eV at 300 K. A theoretical framework is derived to evaluate the cell performance. The absorption of the incident radiation, which can either be from a black-body, a gray-body or a laser, is investigated using the generalized transfer matrix method thereby considering the mixed coherent/incoherent layer stacking, and the $500\,\mu$m Silicon substrate. Moreover, the intrinsic recombination mechanisms and their importance in a narrow bandgap semiconductor were also investigated and taken into account in our framework. In this regard, the parabolic band approximation and Fermi's golden rule were combined for an accurate estimation of the radiative recombination rate. Based on these analyses, power conversion efficiencies of up to 9% are predicted for $Ge_{0.83}Sn_{0.17}$ thermophotovoltaic cells under black-body radiation at temperatures T_{bb} in the 500-1500 K range. The effects of the heterostructure thickness, surface recombination velocity, and non-radiative carrier lifetime are also elucidated and discussed. To account for the non-ideal experimental parameters, the theoretical incident power density P_{in} is scaled down to compare our GeSn-based TPV to narrow-bandgap III-V based TPV cells for which the values of P_{in} are in the $\mathrm{mW/cm^2}$ range for $T_{bb} \sim 1000$-1500 K, as presented in the table below. Aside from TPV, the theoretical framework is also used to investigate GeSn-based thermoradiative devices or negative illumination photodiodes kept at a constant temperature, and allowed to thermally radiate to a colder environment. Besides, for an experimental investigation of the performance of the group IV-based TPV platform, vertical top-down GeSn p-i-n TPV devices with various mesa diameters were fabricated, and characterized under gray-body radiation, black-body radiation, and infrared laser operation. The performance of these devices was subsequently compared to commercial narrow-bandgap based photodetectors with similar diameters, and under the same operation conditions.



(a)

Parameters	GaInAsSbP p-n-n	InAs p-i-n	InAs p-i-n	GeSn p-i-n	GeSn p-i-n	GeSn p-i-n
E_g(eV)	0.35	0.35	0.35	0.291	0.291	0.291
T_{bb}(K)	1200	$\sim$ 1000	$\sim$ 1200	1200	1500	1500
P_{in}(W/cm^2)	0.5	0.72	0.32	0.3	0.7	26.96
J_{SC}(A/cm^2)	0.29	0.89	0.21	0.203	0.485	18.68
V_{OC}(V)	0.028	0.06	0.018	0.075	0.097	0.195
FF(%)	33	37	28.09	42.82	47.81	62.47
η(%)	0.53	3	0.33	2.16	3.22	8.45
P_{out}(mW/cm^2)	2.66	21.6	1.05	6.48	22.54	2.28×10^3
Ref	[11]	[12]	[3]	This work	This work	This work

(b)

Fig. 1. (a) Schematic illustration of the $Ge_{1-y}Sn_y$ TPV cell. (b) Performance parameters of current narrow bandgap TPV cells [1]

References

[1] G. Daligou et al., IEEE Journal of Photovoltaics, vol. 13, no. 5, pp. 728-735 (2023).