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Electricity generation from thermal irradiation governed by GaSb active layer

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ABSTRACT

Electricity generation from thermal irradiation governed by GaSb diode has been systematically investigated in its normal and inverted configuration. It is demonstrated here that there is a critical base doping, 3×10^{17} cm^{-3}, for the normal structure, and the superior output performance of p^+/n structure with low base-doping would completely be switched to the n^+/p structure when base doping larger than this critical one. Moreover, a spectrum-independent optimal doping concentration, $N_a = 1.5 \times 10^{17}$ cm^{-3}, is also observed for n^+/p structure, and no doping-dependent thickness compensation between emitter and base layer can be observed for the inverted structure. To save the material consumption and device cost, the reasonable active layer can be constructed by 100–200 nm emitter and 5–7 μm base, offering the useful guideline to fabricate the GaSb cell on the economical but lattice-mismatched hetero-substrate.

1. Introduction

As a promising method to recycle the waste heat from the environment, thermophotovoltaic (TPV) has received increasingly interest in recent years due to its potential applications in portable electronic device, terrestrial and space power supply [1–3]. In typical TPV scheme, photovoltaic cells made by narrow band-gap semiconductors like InGaAs [4] and GaSb [5] were employed to convert the infrared thermal irradiation into electric power, and rapid development in cell fabrication has been demonstrated in the past years. For instance, Wernsman et al. [6] has implemented an InGaAs-based TPV system with the radiant heat conversion efficiency (η) greater than 20%, and a series of GaInAsSb cell [7,8] as well as impressive system demonstration [9] have also been reported. Even in a much simple strategy, high-quality GaSb cell can be simply obtained by directly diffusing zinc into *n*-type GaSb substrate [10]. Advanced by those experimental as well as theoretical achievements [11–13], a promising prospect can thus be expected for TPV.

However, in the viewpoint of scalable industrial application, the mentioned schemes would inevitably suffer a high-cost dilemma due to the limited reserves of alloy elements in earth. For InGaAs-based cell, due to the absence of lattice-matched substrate, the production of TPV cell was generally performed on the expensive InP substrate, and the complex buffer layer or quantum device structure [14–16] should be employed in order to achieve better electricity generation and cell quality, indicating its deficiency in industrial applications. For GaSb-based cell, although the high-quality zinc-diffused cell can be easily accessed, it is still highly necessary to reduce the consumption of GaSb substrate. In this context, fabricating or transferring the cell active layer onto the economical hetero-substrate might be a preferable route. On the basis of GaSb/GaAs system of 7% lattice mismatch, recent experiments [17,18] have demonstrated the possibility to obtain high quality, free electric-active defect GaSb epitaxial film onto the large mismatched hetero-substrates. Thus, for this promising scheme, besides the detailed investigation on the effect of possible interface misfit-defect on the device performance, it is also indispensable to reveal the device optimum structure as well as the resulting output characteristic versus the variation of various system parameters. However, little effort has been paid on this point at present.

In this paper, by extracting the real hetero-epitaxial TPV device as an ideal diode, the electricity generation from thermal irradiation dominated by GaSb active layer has been investigated. After systematically simulating optimum layer structure as well as its output versus the variation of different model parameters, it is demonstrated here that there is a universal critical base doping,

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$N_a = 1.5 \times 10^{17}$ cm^{-3}, for active layer in its n$^+$/p configuration, and the superior output for p$^+$/n configuration in low base doping regime would be inferior to n$^+$/p one with the increasing base doping, providing useful guideline to fabricate experimentally GaSb cell on the hetero-substrate.

2. Model and equation

In our calculation, we extracted cell active layer structure from its real background as a planar diode consisting of a p-type layer and n-type one. Several realistic components, the front electrode shading, surface optical reflection loss, series and parallel resistance, and back surface reflector, of real device have been neglected here since little established data [19,20] can be accessible for GaSb-based material. Following the classical solar cell model [21], the device current density (J) – voltage (V) characteristic can be modeled by

$$J = J_{sc} - J_o[\exp(qV/k_BT) - 1] \quad (1)$$

with q, k_B, and T denoting, respectively, the electron charge, Boltzmann constant, and cell temperature. The dark current density J_o can be further determined from the specific active layer [21] as

$$\mathrm{J_o} = \frac{\mathrm{qn_i^2D_h}}{\mathrm{N_dL_h}}\left\{\frac{\mathrm{Sinh(H/L_h)} + \mathrm{(S_BL_h/D_h)Cosh(H/L_h)}}{\mathrm{Cosh(H/L_h)} + \mathrm{(S_BL_h/D_h)Sinh(H/L_h)}}\right\} + \frac{\mathrm{qn_i^2D_e}}{\mathrm{N_aL_e}}\left\{\frac{\mathrm{Sinh(X/L_e)} + \mathrm{(S_FL_e/D_e)Cosh(X/L_e)}}{\mathrm{Cosh(X/L_e)} + \mathrm{(S_FL_e/D_e)Sinh(X/L_e)}}\right\} \quad (2)$$

where $\mathrm{N_{d/a}}$ is the donor/acceptor concentration in n/p-type layer, $\mathrm{D}(L)_{\mathrm{e/h}}$ is the minority electron(e)/hole(h) diffusion coefficient (length) in p/n-type region, X(H) is the thickness of quasi-neutral region of n(p)-type layer, n_i is the intrinsic carrier concentration of host material, and S_F (S_B) is the surface recombination rates at the front (back) surface.

By applying the Einstein relationship, $D_{\mathrm{e/h}}(= k_BT\mu_{\mathrm{e/h}}/q)$ can be expressed as a function of carrier mobility $\mu_{\mathrm{e/h}}$, which can be further determined from classical Caughey–Thomas model [22,23] as

$$\mu_{\mathrm{e/h}}\left(\mathrm{N}_{a/\mathrm{d}}\right) = \mu_{\mathrm{min,e/h}} + \left(\mu_{\mathrm{max,e/h}} - \mu_{\mathrm{min,e/h}}\right)\left[1 + \left(\mathrm{N}_{a/d}/\mathrm{N}_{\mathrm{ref,e/h}}\right)^{\alpha_{\mathrm{e/h}}}\right]^{-1} \quad (3)$$

where $\mu_{\mathrm{min,e/h}}$ and $\mu_{\mathrm{max,e/h}}$ denotes the value of carrier mobility at the very low and high doping extreme, $N_{ref,\mathrm{e/h}}$ is the doping concentration at which the mobility is decreased to half the value it reaches at low doping at room temperature, and $\alpha_{\mathrm{e/h}}$ is the suggested fitting parameters. To calculate $L_{\mathrm{e/h}}(= \sqrt{D_{\mathrm{e/h}}\tau_{\mathrm{e/h}}})$, three dominant recombination mechanisms, namely radiation recombination, trap-assisted recombination, and Auger recombination, are considered. The minority carrier lifetime $\tau_{\mathrm{e/h}}$ can thus be determined as

$$\tau_{\mathrm{e/h}}^{-1} = \left(\mathrm{B_{opt}N_{a/d}}\right)^{-1} + \tau_{\mathrm{SRH,e/h}}^{-1} + \left(\varLambda \mathrm{N_{a/d}^2}\right)^{-1} \quad (4)$$

with $\mathrm{B_{opt}}$, $\tau_{\mathrm{SRH,e/h}}^{-1}$, and $\varLambda$ being the radiation recombination coefficient, trap-assisted recombination lifetime, and Auger recombination coefficient, respectively.

Integrating the incident blackbody spectrum $\phi(\lambda)$ with the structure-dependent internal quantum efficiency $QE(\lambda)$, J_{sc} can be derived [21] as

$$J_{sc} = \int_0^{\lambda_m} q\phi(\lambda)QE(\lambda)d\lambda \quad (5)$$

where λ and λ_m, respectively, are the incident wavelength and cell cutting-wavelength, $\phi(\lambda) = 2\pi\lambda^{-4}[\exp(hc/k_BT) - 1]^{-1}$ with Plank's constant h and the speed of light c, and the explicit expression for $QE(\lambda)$ can be found in the classical textbook [21]. Noteworthy, in this study, the optical absorption coefficient was taken from our model calculation [24] reported previously.

After obtaining the device J–V characteristic, the device efficiency η can be calculated from dividing the maximum power density of J–V curve by the total radiation power σT_{BB}^4, where σ and T_{BB} are Stefan–Boltzmann constant and blackbody emitter temperature, respectively. In Table 1 we have tabulated the needed model parameters for this work.

3. Results and discussions

Generally, the specific structure of diode active layer can be constructed in its p-on-n or n-on-p configuration, and depending on the high-doped layer in the front (emitter) or rear (base) layer of diode, a normal or inverted structure can be further obtained in each configuration. By assuming typical spectrum illumination $T_{BB} = 1200$ K and taking doping profiles as 10^{18}(10^{17}) cm^{-3} for high (light)-doped layer, these configuration-dependent structure characteristics were firstly examined as shown in Fig. 1(2) for n-on-p (p-on-n) configuration. Obviously, as can be seen from the Fig. 1, a better electricity generation can be expected for the normal structure and an economical structure can be constructed by reducing the material consumption while preserving good output

Table 1
Model parameters for the device simulation.

Parameters	value	Refs.
Intrinsic carrier concentration n_i	1.405×10^{12} cm^{-3}	[23]
Radiation recombination coefficient $\mathrm{B_{opt}}$	8.5×10^{-11} cm^{-3} s^{-1}	[19]
Auger recombination coefficient $\varLambda$	5×10^{-30} cm^6 s^{-1}	[25]
Trap-assisted recombination lifetime of electron $\tau_{SRH,n}$	10 ns	[19]
Trap-assisted recombination lifetime of hole $\tau_{SRH,p}$	600 ns	[20,25]
Electron mobility in p-type layer μ_e	$\mu_e = 1050 + \frac{4600}{1 + \left(\frac{N_a}{2.8 \times 10^{17}}\right)^{1.05}}$	[24]
Hole mobility in n-type layer μ_h	$\mu_h = 190 + \frac{685}{1 + \left(\frac{N_d}{9 \times 10^{17}}\right)^{0.65}}$	[24]
Front surface recombination rate S_F	10^6 cm s^{-1}	[20,25]
Back surface recombination rate S_B	10^2 cm s^{-1}	This work