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Effect of Temperature on the Bandwidth and Responsivity of Uni-Traveling-Carrier and Modified Uni-Traveling-Carrier Photodiodes

Dong-Hwan Jun[1], Jae-Hyung Jang[1], and Jong-In Song[1]

[1]Dept. of Information and Communications, GIST,
1 Oryong-dong Buk-gu, Gwangju, 500-712, Korea
+82-62-970-2208, +82-62-970-2204, e-mail: jisong@gist.ac.kr

1. Introduction

InGaAs PIN photodiodes have been widely used for high speed optoelectronic conversion applications. However, they are inappropriate in harsh environments, especially in environments having elevated temperatures since the bandwidth performance of PIN photodiode can be deteriorated at high temperatures by the reduced carrier saturation velocity induced by increased lattice vibration. Recently, uni-traveling-carrier (UTC) photodiodes have come into the spotlight due to their inherent high speed and high output power characteristics [1]. The bandwidth of UTC photodiode is determined by a different physical mechanism from that of the conventional PIN photodiodes and thus can have different characteristics in high temperature environments. Researches on bandwidth of PIN photodiode and responsivity of UTC photodiode at low temperature were reported [2], [3]. However, temperature effect on both bandwidth and responsivity of photodiode were not reported. In this paper, temperature dependent dc and microwave performances of a UTC photodiode and a modified uni-traveling-carrier (MUTC) photodiode were analytically and experimentally investigated.

2. Experiments

Figure 1 shows the schematic cross sections of the top-side illuminated UTC photodiode and MUTC photodiode epi-structures that are described in detail elsewhere [4]. The UTC photodiode consists of a 300 nm-thick p-type photo-absorption layer and 400 nm-thick undoped collection layer. The MUTC photodiode consists of a 300 nm-thick p-type photo-absorption layer and 400 nm-thick undoped photo-absorption layer.

For the measurement of temperature dependent characteristics of photodiodes, on-wafer measurement using a chuck equipped with a temperature controller was performed. Frequency responses of the photodiodes were measured on wafer by using the optical heterodyne method [4]. Frequency dependent losses due to a RF probe, a RF cable, and a bias tee were taken into account for the calibration of the measurement system. One-port scattering parameter of the RF probe was measured to calibrate the loss using open-short-load patterns [5].

3. Responsivity and Bandwidth

The absorption coefficient of a semiconductor can be approximated as: $\alpha \cong 2\times 10^4 \cdot (E_p - E_g(T))^{1/2}$, where E_p and E_g are the incident photon energy and the energy gap of the photo-absorption material and expressed in eV [6]. The photo-absorption coefficient is a function of temperature since the energy band gap reduces as temperature increases.

Figure 2 shows the measured and calculated responsivities of the photodiodes as a function of temperature and normalized by the value at 300 K. The responsivities were measured for the 1550 nm optical signal under the bias voltage of -2 V. To consider the dark current, the measured responsivity was obtained using $R=(I-I_{dark})/P_{opt}$, where I, I_{dark}, and P_{opt} are the measured current, dark current, and input optical power, respectively. As shown in the Fig. 2, the measured responsivities of UTC and MUTC photodiodes are proportional to temperature. The normalized responsivities of the UTC and MUTC photodiodes at 400 K (0.33 A/W and 0.58 A/W) were increased by 15 % and 11 % compared with those at 300 K, respectively.

The bandwidth of the UTC photodiode with thick (300 nm) p-type photo-absorption layer is expressed as $f_{3dB} \sim 3D_e/(2\pi \cdot W_a^2)$, where D_e and W_a are the electron diffusion coefficient and the thickness of the p-type photo-absorption layer, respectively [1]. The electron diffusion coefficient is a function of temperature and it can be written as using the Einstein relation:

$$f_{3dB} \sim 3k_B \cdot \mu_e(T) \cdot T/(2\pi \cdot q \cdot W_a^2), \tag{1}$$

where k_B, $\mu_e(T)$, and q are the Boltzmann constant, the electron mobility in p-InGaAs, and the elementary charge, respectively. The electron mobility, μ_e, in a p-type InGaAs layer with high doping concentration is constant above 300 K since the InGaAs has a GaAs-like energy band structure and scattering properties [6]. Therefore, the bandwidth of the UTC photodiode can be proportional to temperature.

The bandwidth of MUTC photodiode has similar characteristic to that of PIN photodiode [4]. The bandwidth of a PIN photodiode is expressed as $f_{3dB} \sim 0.55\ \upsilon_{hsat}(T)/W_b$, where $\upsilon_{hsat}(T)$, and W_b are the average hole velocity and the thickness of the depleted InGaAs layer, respectively [7]. The average hole velocity reduces as temperature increases due to increased lattice vibration resulting the reduction of bandwidth of PIN photodiodes. Therefore, it is anticipated that the bandwidth of the MUTC photodiode can be reduced at high temperature.

Figure 3 shows the measured relative response of the UTC and MUTC photodiode for the input optical power of -6 dBm under the bias voltage of –2 V, where the simulated RC limited bandwidth was over 95 GHz. The bandwidth of MUTC photodiode was reduced by elevated temperature as shown in the Fig. 3. On the contrary, the bandwidth of UTC photodiode increases as the temperature increases. The effect of temperature on the bandwidth of the UTC and MUTC photodiodes are shown in the Fig. 4. The bandwidth of UTC photodiode at high temperature is higher than that of room temperature in spite of thermally increased lattice vibration. This phenomenon is ascribed to the thermally increased electron diffusion coefficient in the p-type photo-absorption layer of UTC photodiode as anticipated in (1).

4. Conclusions

In conclusion, the temperature dependent characteristics of a UTC photodiode and a MUTC photodiode in terms of bandwidth and responsivity were investigated. Their responsivities had increased. Interestingly, the bandwidth of UTC photodiode increased up to 40 % as the temperature increased due to the increased electron diffusion coefficient in the p-type photo-absorption layer.

Acknowledgements

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Layer	Doping	UTC-PD	MUTC-PD
$In_{0.53}Ga_{0.47}As$	P:$1\times10^{19}cm^{-3}$	60nm	
$In_{0.53}Al_{0.03}Ga_{0.44}As$	P:$1\times10^{19}cm^{-3}$	15nm	
$In_{0.53}Ga_{0.47}As$: photo-absorption layer	P:$1\times10^{18}cm^{-3}$	300nm	
	undoped	10nm	400nm
$In_{0.53}Al_{0.03}Ga_{0.44}As$	undoped	10nm	10nm*
InP	undoped	380nm	0nm
InP	N:$5\times10^{18}cm^{-3}$	50nm	
$In_{0.53}Ga_{0.47}As$	N:$1\times10^{19}cm^{-3}$	20nm	
InP	N:$1\times10^{19}cm^{-3}$	400nm	
Semi-insulated InP Substrate			

Figure 1. Epi-structures of the UTC photodiode and MUTC photodiode (*- N: 5×1018 cm-3)

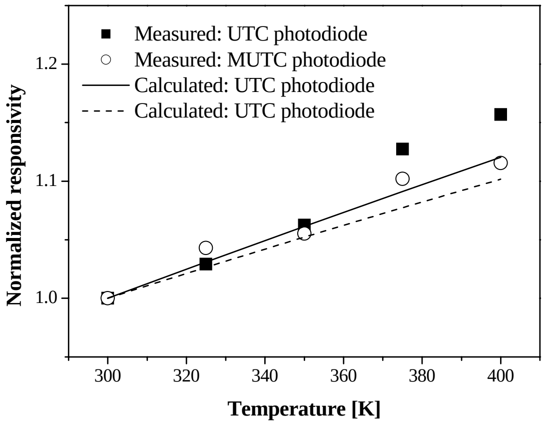

Figure 2. Normalized responsivities of photodiodes with input optical power 1 mW under the bias voltage -2V.

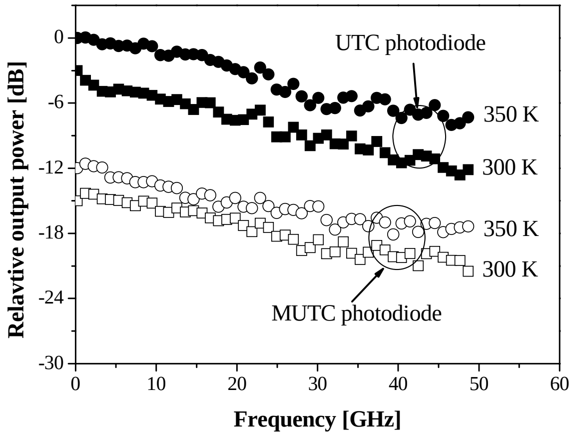

Figure 3. Relative frequency responses of the photodiodes with the diameter of 11 μm under the bias voltage -2 V. (3-dB offset for clarity).

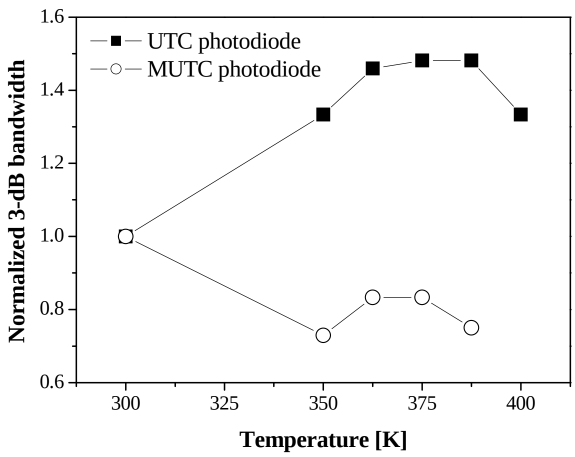

Figure 4. Normalized bandwidths of photodiodes as a function of temperature.