Optoelectronics

Small signal analysis of an infrared imaging device based on equivalent circuit model

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Abstract. This paper presents an analytical model of an infrared thermal imaging device. This device is composed of a Quantum Well Infrared Photodetector (QWIP), a Heterojunction Bipolar transistor (HBT) and a Light Emitting Diode (LED). It is called as QWIP-HBT-LED Optoelectronic Integrated Device. The device is modeled based on its equivalent circuit by considering a nonlinear gain HBT, early effect. Analytical expressions describing the current time response, rise time, and output derivative as a measure of device speed have been derived. The numerical results show that the transient performance of this device version is enhanced by the injected current from QWIP to the base of HBT, also the output current is increased with the increase of the gain and early coefficient of HBT, on the other hand, it degrades when the base recombination factor of HBT or the load resistance is increased. Also, the rise time increases when the current gain or the early coefficient is increased. This type of models can be exploited as a pixel in thermal image processing applications.

Keywords: analytical model, quantum well infrared photodetector, heterojunction bipolar transistor, LED, optoelectronic integrated device.

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I. Introduction

The thermal imaging devices based on conversion from long-wave infrared (IR) light to shorter-wave radiation have attracted attention and have been intensively exploited in different applications. Some of these applications are low-cost and large format IR/terahertz (THz) imaging, high-efficiency solar cells, and sensitive biological imaging [1].

For optical image processing applications, it is necessary to focus on devices and components that can detect, process and transmit the information with great adaptability and better efficiency. Integration of a quantum well infrared photodetector (QWIP) and light emitting diode (LED) is one of the effective methods to obtain thermal integrated device to be used as a pixel sensitive to far or middle infrared radiation with near infrared output [2]. The external quantum efficiency of LED can be enhanced by the re-emission of photons generated in the active layer with directions outside the critical cone of angles.

The major device parameters influencing the near infrared (NIR) light lateral spread and the LED external efficiency of QWIP integrated with LED (QWIP-LED) imaging device has been already studied theoretically [3]. The structures coupling QWIP and LED that use photon recycling effects are achieved by optimizing the thickness of the LED active layer to get high external quantum efficiency. The previous studies focused on fabrication and the analysis of static device performances [4, 5], however they did not analyze the transient behavior of the device.

An evaluation of another effective type of a thermal imaging structure based on integration of QWIP, a heterostructure bipolar transistor and LED for up-conversion of middle infrared into near infrared (visible) radiation has been developed [6]. It was shown that the external output current can be of the order of unity that can provide significant advantages of QWIP-HBT-LED based focal plane arrays (FPAs) over FPAs of the other types.

A theoretical modeling of the transient behavior of QWIP-HBT-LED was developed being based on the convolution theorem [7]. There it was shown that the overall transient behavior is approximately the same as the constituent device with the lowest cutoff frequency.

By contrast, the present article focuses on analyzing the proposed model based on its equivalent circuit. This equivalent circuit modeling gives a more detailed analysis regarding the output current in terms of its components. Also, the equivalent circuit modeling is a very useful way to understand or predict the operation and behavior of the developed model, where the modeling requires more understanding to represent the model structure into ideal simple circuit elements.

Numerical simulation of the carefully designed Au Rods with transmittance in the wavelength range 7…9 µm exceeds 64% and was developed by [8]. This type of devices are able to be integrated to other optical interconnection devices, so a highly efficient dielectric infrared coupler for QWIPs operating in the spectral range 14 to 16 µm was designed [9]. QWIP with high image uniformity and stability suitable for various applications, namely: handheld cameras, gas detection and microsatellite for remote sensing were developed in [10].

Operation of this device can be explained as follows: the input light is converted to photo-generated carriers through QWIP, the QWIP output electric signal is amplified by the HBT, and LED is driven by the output amplified signal injected from the HBT and emits an intensified light of near infrared or visible radiation.

Fig. 1a shows a schematic structure of QWIP-HBT-LED. QWIP is composed of n^+-n-n^+ layers, HBT is composed of p^+-n^+-p^+ layers and LED is composed of p^+-n^+layers. The QWIP collector layer is considered as the base of HBT, while collector serves as the LED active region. The paper is organized as follows: formulation of the specified parameters which describe the transient response, derivative and rise time are presented in section 2. The generated curves as results are outlined and discussed in Section 3. Finally, conclusion of this work and some important notes for the continuity of the research in this topic has been discussed in Section 4.

2. Theoretical analysis

Consider the equivalent circuit of the device shown in Fig. 1b. In the following derivations, the feedback injected current from LED in the HBT base is neglected, the injected current from QWIP can be modeled as a current source connected to the base. From the equivalent circuit, the current can be modeled as follows.

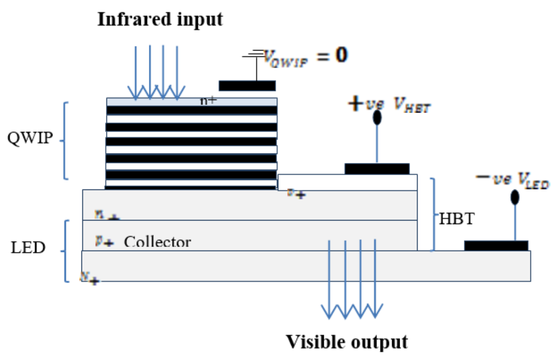

Fig. 1a. Schematic structure of an integrated QWIP-HBT-LED device.

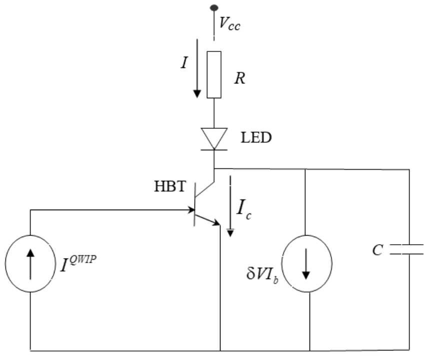

Fig. 1b. Equivalent circuit of QWIP-HBT-LED optoelectronic integrated device (OEID).

$$I = I_c + \delta I_b V - RC\frac{dI}{dt}, \tag{1}$$

where I_c is the collector current, I_b is the base current, δ is the early effect factor between base and collector, and $\delta I_b V$ is the current resulting due to early effect.

Assuming non-linear current gain of HBT,

$$I_c = \frac{\beta_0}{1 + b_r I_c^{-0.5}} I_b, \tag{2}$$

where b_r is the base recombination factor, β_0 is the common emitter current gain.

For a small current value, $1 \prec b_r I_c^{-0.5}$, then $I_c = \left(\frac{\beta_0 I_b}{b_r}\right)^2$.

Substituting I_c into Eq. (1) and setting $V = V_{cc} - IR$, one can obtain

$$\frac{dI}{dt} + I\left(\frac{1}{RC} + \frac{\delta I_b}{c}\right) = \frac{1}{RC}\left(\left(\frac{\beta_0 I_b}{b_r}\right)^2 + \delta I_b V_{cc}\right). \tag{3}$$

Solving the above differential equation with the use of Convolution Theorem described in [11, 12] or any way.

$$I = \int_0^t \frac{1}{RC}\left[\left(\frac{\beta_0 I_b}{b_r}\right)^2 + \delta I_b V_{cc}\right] e^{-\left(\frac{1}{RC}+\frac{\delta I_b}{c}\right)\lambda} d\lambda. \tag{4}$$

Then

$$I = Ae^{-\left(\frac{1}{RC}+\frac{\delta I_b}{c}\right)t} + \frac{\left(\frac{\beta_0 I_b}{b_r}\right)^2 + \delta I_b V_{cc}}{1 + \delta I_b R}, \tag{5}$$

where

$$A = -\frac{\left(\left(\frac{\beta_0 I_b}{b_r}\right)^2 + \delta I_b V_{cc}\right)}{(1 + \delta I_b R)} \tag{6}$$

The injected QWIP photocurrent through the base is given from Ref [6] as follows.

$$I^{QWIP} = I_b = \frac{\sigma \sum_D}{\left(1-\alpha^{QWIP}\right)} \exp\left(\frac{V^{HBT}}{V_{ph}}\right) I_\omega , \tag{7}$$

where σ is the cross-section of electrons sheet leaving the QW barriers, $\sum_D$ is the donor sheet concentration in QWs, α^{QWIP} is the QW layer absorption coefficient, V^{HBT} is the HBT voltage drop, V_{ph} is the QW active region voltage drop and I_ω is the incident photon intensity. The transient current inside the device after introducing I_b can be written as

$$I = C\left(1 - e^{-\left(\frac{1}{RC} + \frac{\delta\left(\frac{\sigma \sum_D}{\left(1-\alpha^{QWIP}\right)} \exp\left(\frac{V^{HBT}}{V_{ph}}\right) I_\omega\right)}{c}\right)}\right), \tag{8}$$

where

$$C = \frac{\left(\left(\frac{\beta_0\left(\frac{\sigma \sum_D}{\left(1-\alpha^{QWIP}\right)} \exp\left(\frac{V^{HBT}}{V_{ph}}\right) I_\omega\right)}{b_r}\right)^2 + \delta\left(\frac{\sigma \sum_D}{\left(1-\alpha^{QWIP}\right)} \exp\left(\frac{V^{HBT}}{V_{ph}}\right) I_\omega\right) V_{cc}\right)}{\left(1 + \delta\left(\frac{\sigma \sum_D}{\left(1-\alpha^{QWIP}\right)} \exp\left(\frac{V^{HBT}}{V_{ph}}\right) I_\omega\right) R\right)} . \tag{9}$$

In the steady state, the output current is derived as

$$I_{t=\infty} = C = \frac{\left(\left(\frac{\beta_0\left(\frac{\sigma \sum_D}{\left(1-\alpha^{QWIP}\right)} \exp\left(\frac{V^{HBT}}{V_{ph}}\right) I_\omega\right)}{b_r}\right)^2 + \delta\left(\frac{\sigma \sum_D}{\left(1-\alpha^{QWIP}\right)} \exp\left(\frac{V^{HBT}}{V_{ph}}\right) I_\omega\right) V_{cc}\right)}{\left(1 + \delta\left(\frac{\sigma \sum_D}{\left(1-\alpha^{QWIP}\right)} \exp\left(\frac{V^{HBT}}{V_{ph}}\right) I_\omega\right) R\right)} \tag{10}$$

The rise time of the photocurrent inside the optoelectronic integrated devices is defined as the time required for *i(t)* to rise to 0.9 of its final value, by solving Eq. (8). The rise time can be given as

$$T = RC \frac{H}{\left(1 + \delta R\left(\frac{\sigma \sum_D}{\left(1-\alpha^{QWIP}\right)} \exp\left(\frac{V^{HBT}}{V_{ph}}\right) I_\omega\right)\right)}, \tag{11}$$

where,

$$H = \ln\left(\frac{1-0.9I_f\left(\left(1+\delta\left(\frac{\sigma\sum_D}{\left(1-\alpha^{QWIP}\right)}\exp\left(\frac{V^{HBT}}{V_{ph}}\right)I_\omega\right)R\right)\right)}{\left(\left(\frac{\beta_0\left(\frac{\sigma\sum_D}{\left(1-\alpha^{QWIP}\right)}\exp\left(\frac{V^{HBT}}{V_{ph}}\right)I_\omega\right)}{b_r}\right)^2+\delta\left(\frac{\sigma\sum_D}{\left(1-\alpha^{QWIP}\right)}\exp\left(\frac{V^{HBT}}{V_{ph}}\right)I_\omega\right)V_{cc}\right)}\right) \quad (12)$$

When $I_f = I_{t=\infty} = \frac{\left(I_c+\delta I_b V_{cc}\right)}{\left(1+\delta I_b R\right)}$, then $T = \frac{2.3}{\left(\frac{1}{RC}+\frac{\delta\left(\frac{\sigma\sum_D}{\left(1-\alpha^{QWIP}\right)}\exp\left(\frac{V^{HBT}}{V_{ph}}\right)I_\omega\right)}{c}\right)}$. (13)

The derivative of the device output current with respect to time denoted by υ is expressed by $\upsilon(t) = \frac{dI(t)}{dt}$, which describes how fast the output current changes with time, this quantity can be expressed as

$$\upsilon(t) = \frac{dI(t)}{dt} = C\left(e^{-\left(\frac{1}{RC}+\frac{\delta\left(\frac{\sigma\sum_D}{\left(1-\alpha^{QWIP}\right)}\exp\left(\frac{V^{HBT}}{V_{ph}}\right)I_\omega\right)}{c}\right)t}\right). \quad (14)$$

When the current through the device is high, *i.e.*, $1 \succ b_r I_c^{-0.5}$, the above expressions will be the same, except $I_c = \left(\frac{\beta_0 I_b}{b_r}\right)^2$, and can be replaced by $I_c = \beta_0 I_b$.

3. Results and discussions

The device parameters used in the following calculations are as follows: $b_r = 0.02$, $\delta = 40$, $\beta_0 = 1000$, $R = 50\ \Omega$, $C = 1$ pF, $\Sigma_D = 2\times10^{12}$ cm^{-2}, $\alpha^{QWIP} = 0.6$, $V_{cc} = 5$ V, and $V^{HBT} = 2.4$ V. The input infrared radiation is assumed as a step function in time. The transient response of the output current of QWIP-HBT-LED device at different values of base recombination factor is shown in Fig. 2. It can be seen that the output current increases with time until approaches a definite and stable value. This value is dependent on the values of the quantum efficiencies of the constituent devices. Also, the output current is reduced due to base recombination because of lowering the current gain, as it increases the emitter current without increasing the collector current. The increase in base recombination factor reduces the current value at the end of the base in comparison with the value of injected current from the emitter, and it causes reduction in the output current.

The common-emitter current gain is represented by β, it is approximately equal to the ratio of the DC collector current to the DC base current in forward-active region. Fig. 3 shows the transient response of the output current at different values of current gain. It is clear that the output current increases with increasing the current gain, whereas the higher current gain makes the output current to achieve the steady state later than the lower current gain.

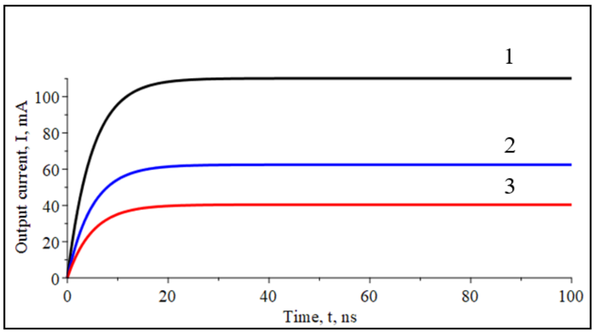

Fig. 2. Transient behavior of QWIP-HBT-LED at different base recombination factors b_r: *1* – 0.03, *2* – 0.04, *3* – 0.05.

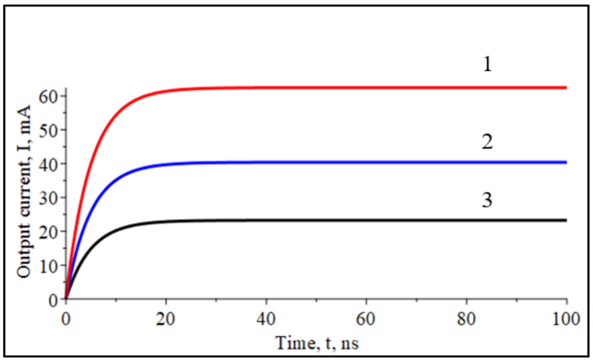

Fig. 3. Transient behavior of QWIP-HBT-LED at different values of HBT gain β: *1* – 1000, *2* – 800, *3* – 600.

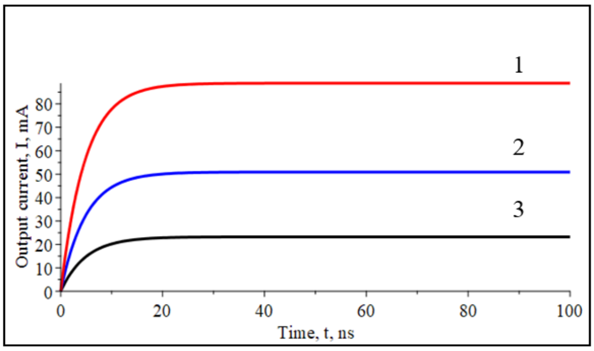

Fig. 4. Transient behavior of QWIP-HBT-LED at different values of the base current I_b: *1* – 20 μA, *2* – 15 μA, *3* – 10 μA.

Fig. 4 shows the effect of the base current on the dynamic response of the output current of the developed model. It can be seen that the output current increases with the increase of base current at any time, the output current increases linearly until achieving the saturate value. With regards to the base current that is equivalent to QW photocurrent, the parameters of quantum wells in the quantum well infrared photodetector are adjusted such that the energy band gap matches the incoming infrared photon energy. Depending on the used material of the quantum wells, the levels of energy of QWIP can absorb radiation in the infrared region.

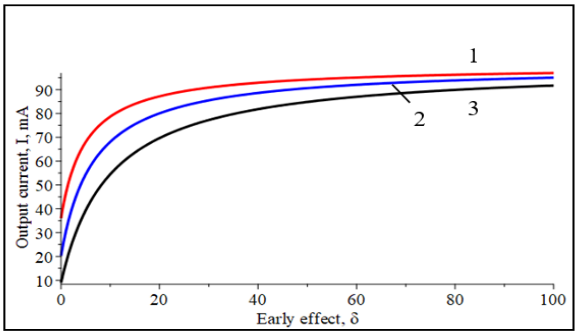

Fig. 5. Variation of the output current against the early effect at different values of the base current I_b: *1* – 20 μA, *2* – 15 μA, *3* – 10 μA.

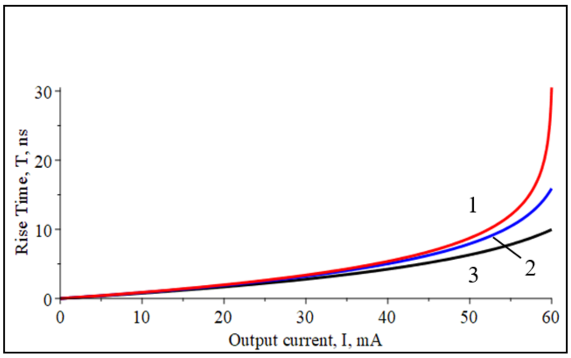

Fig. 6. Dependence of the rise time on the output current at different values of base recombination factor b_r: *1* – 0.04, *2* – 0.03, *3* – 0.02.

Fig. 5 shows the dependence of the output current on the early effect. The early effect is variation in the width of the base due to variation in the applied base-collector voltage. If a small increment of the base emitter voltage takes place, the junction of collector-base becomes more reverse-biased, this causes the depletion region of this junction to become wider, which in turn decreases the effective width of the base, whereas the physical width of the base region does not alter. The increase of this voltage increases the reverse base-collector depletion region, which yields to decrease the base width and the current gain as well as the output current.

The dependence of the rise time of the device on the output current is shown in Fig. 6. When the final value of output current is increased, the rise time to this value is also increased, because the difference between the initial and final value is increased which requires more time to reach this final value and hence the increase in rise time of the device. Also, the lower base recombination factor causes an enhancement of the output current, and the rise time is increased as a result.

A plot of frequency response of the developed device at different values of cutoff frequency of HBT is shown in Fig. 7. The frequency response measures the magnitude of the output signal as a function of frequency

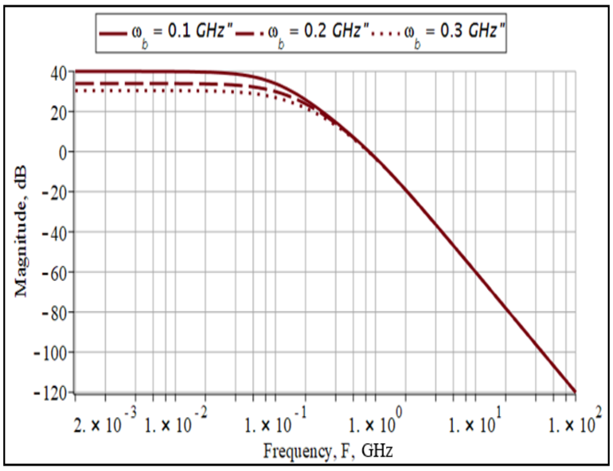

Fig. 7. Frequency response of QWIP-HBT-LED at different values of ω_b.

in comparison to the frequency of the input signal, and is used to characterize the dynamic response of the device. Also, it is shown from the plot, the amplitude remains nearly constant for frequencies below the HBT cutoff frequency and begins to decrease at higher frequencies. In addition, the bandwidth increases with the increase of the HBT cutoff frequency.

4. Conclusion and future work

Analytical modeling of the transient performance of an infrared imaging device has been presented. The device under study is composed of a quantum well infrared photodetector (QWIP), a heterojunction bipolar transistor (HBT) and a light emitting diode (LED). The modeling is based on the equivalent circuit model. The analytical expressions describing the transient performance have been derived. The results show that the current gain of HBT causes an enhancement of the output current, and the rise time is increased as a result. The base recombination and early effect have a major influence on the behavior of the output current. The early effect causes enhancement of the output current, while base recombination causes reduction in the output current. These devices can be exploited in infrared solar cells and biological imaging sensors. As a future extension to this study, the modeling of this device by using its equivalent circuit is planned to show the effect of all interesting parameters on the resolution characteristics.

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Saad M.H.: Methodology, Investigation, Visualization, Data Curation, Writing - Review & Editing.

Аналіз малих сигналів за допомогою інфрачервоного пристрою формування зображення на основі моделі еквівалентної схеми

Анотація. У цій роботі представлено аналітичну модель інфрачервоного тепловізора. Цей пристрій складається з інфрачервоного фотодетектора з квантовою ямою (QWIP), біполярного транзистора з гетеропереходом (HBT) та світловипромінюючого діода (LED). Він називається оптоелектронним інтегрованим пристроєм QWIP-HBT-LED. Пристрій моделюється на основі еквівалентної схеми з урахуванням нелінійного підсилення HBT первинного ефекту. Отримано аналітичні вирази, що описують поточну тимчасову характеристику, час наростання та похідну струму на виході як міру швидкодії пристрою. Чисельні результати показують, що перехідні характеристики цієї версії пристрою покращуються за рахунок струму, що подається від QWIP до бази HBT, а також вихідний струм збільшується зі збільшенням коефіцієнта підсилення і первинного коефіцієнта HBT, з іншого боку, це погіршується, коли базовий фактор рекомбінації HBT або опір навантаження збільшуються. Також, час наростання збільшується зі збільшенням приросту струму чи раннього коефіцієнта. Цей тип моделей можна застосовувати як піксель у програмах для обробки теплових зображень.

Ключові слова: аналітична модель, інфрачервоний фотоприймач із квантовими ямами, гетероперехідний біполярний транзистор, світлодіод, оптоелектронний інтегральний пристрій.
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