Device Model of Integrated QWIP-HBT-LED Pixel for Infrared Focal Plane Arrays

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Abstract

We propose and evaluate a novel device based on integration of quantum well infrared photodetector (QWIP), heterostructure bipolar transistor (HBT), and light emitting diode (LED) for up-conversion of middle infrared into near infrared (visible) radiation. Its operation is associated with intersubband absorption of middle infrared radiation in the QWIP, amplification of the QWIP output electric signal in the HBT and emission of near infrared or visible radiation from the LED driven by the current injected from the HBT. The integrated QWIP-HBT-LED device can serve as a highly effective pixel for infrared focal plane arrays.

1. Introduction

In a conventional focal plane array (FPA), the signal from each photodetector in the array is fed into an external Si read-out integrated circuit, which integrates and transfers it into a video output. This scheme requires to form a bond between each photodetector and corresponding Si circuit, which translates in a large FPA to hundreds of thousands of bonds. Such hybridization of dissimilar materials makes the system extremely expensive and unreliable, in particular, because it is subjected to large temperature variations. Recent progress in infrared photodetector technology based on A_3B_5 quantum well structures has led to the development of large FPAs [1], which constitute an attractive alternative to the conventional schemes implementing narrow-bandgap materials (e. g., HgCdTe). Narrow-bandgap materials are well known to be more difficult to grow, process and fabricate into devices comparing to more mature A_3B_5 materials. Though the performance of intraband quantum well photodetectors (QWIPs) is slightly lower than that of interband HgCdTe photodiodes, the maturity of A_3B_5 materials and technologies can potentially solve the problems of nonuniformity, low yield and high cost of large HgCdTe FPAs. As shown some time ago [2, 3], a QWIP integrated with a light-emitting diode (LED) can be used as a pixel sensitive to far or middle infrared radiation with near infrared output. Infrared imaging devices based on integration of QWIPs and LEDs can consist of a large array of such pixels or be based on a uniform (in lateral direction) heterostructure without its separation on individual pixels. The pixelless imaging devices were extensively studied both experimentally and theoretically [4-7]. Usually such QWIP-

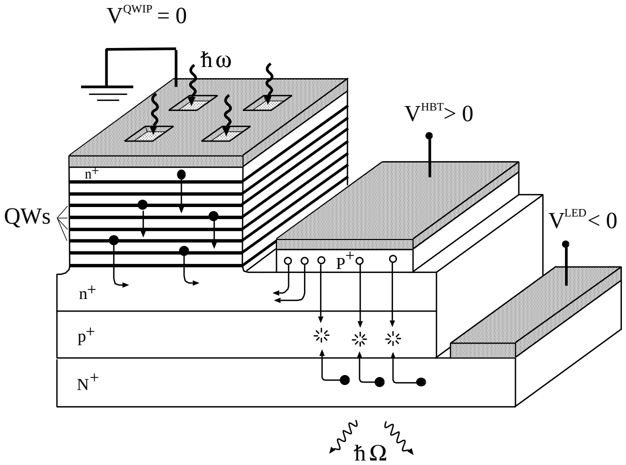

Figure 1. Schematic structure of an integrated QWIP-HBT-LED pixel.

LED pixelless imaging devices are supplied by CCD camera. This design makes infrared imaging devices extremely simple and inexpensive in processing. Unfortunately, the direct integration of QWIPs and LEDs suffers from several problems compromising the device performance characteristics such as responsivity and signal-to-noise ratio.

Another approach is to design pixels for FPAs which comprise not only a QWIP and a LED but a transistor amplifying the signal output from the QWIP part before its input into the LED part of this pixel relaxing the problem of read-out. As shown [8], a QWIP integrated with a hot-electron transistor (HET) can exhibit rather high sensitivity to far or middle infrared radiation. The responsivity of such integrated phototransistor is determined by the product of the QWIP and HET current gains. When the capture probabilities of electrons into QWs in the QWIP portion of the device and into the HET base are small, both current gains can be rather large. Since the current gain of heterostructure bipolar transistors (HBTs) can markedly exceed that of HETs, an integration of a QWIP and an HBT can provide even higher performance. Apart from this, the device based on such an integration can be easily fabricated.

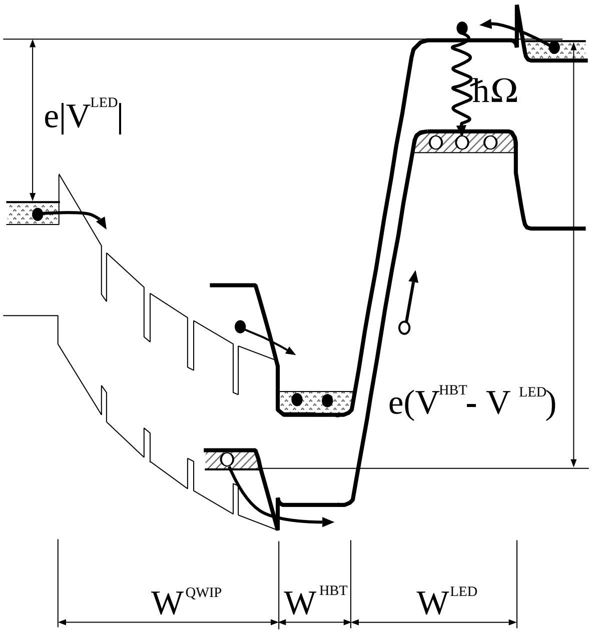

Figure 2. Band diagram of an integrated QWIP-HBT-LED pixel, where thin and bold lines correspond to QWIP- and HBT-LED parts, respectively.

In this communication we propose an integrated QWIP-HBT-LED device which can be used as a pixel for infrared FPAs with optical output, develop its physical-mathematical model, and analyze the output characteristic. In the QWIP-HBT-LED pixel, an electrical signal produced by the middle infrared radiation absorbed in the QWIP due to the intersubband transitions is amplified in the HBT. The amplified current is further injected into the LED which emits near infrared (or, possibly, visible) radiation due to the interband transitions.

2. Device model

The structure of the QWIP-HBT-LED pixel in question and its band diagram are schematically shown in Figs. 1 and 2. The device comprises a n$^+$-N-n$^+$-...-n$^+$-N-n$^+-$ QWIP, P$^+$-n$^+$-p$^+-$ HBT and p$^+$-N$^+-$ LED structures. As seen, the QWIP collector n$^+-$ layer simultaneously serves as the HBT base, whereas the HBT collector p$^+-$ layer plays the role of the LED active region. Alternatively, the QWIP-HBT-LED device can include a p-type QWIP, a N$^+$-p$^+$-n$^+$ - HBT, and a n$^+$-P$^+-$ LED.

Let us denote V^{HBT} and V^{LED} the potentials of the HBT emitter and the LED electron injecting contact with respect to the potential of the QWIP emitter ($V^{QWIP} = 0$). We assume that the applied voltages are chosen in such a way that $V^{HBT} > 0 > V^{LED}$ (see Fig. 2). This corresponds to normal operation of both the QWIP and the HBT. The potential of the QWIP collector and HBT base, φ, is floating.

For the sake of definiteness, we shall approximate the QWIP dark (thermal) current- and photocurrent-voltage characteristics by exponential dependences [9], so the current through the QWIP equals

$$J^{QWIP} = \left(\frac{e}{p}\right)\left[G_{th}\exp\left(\frac{\varphi}{E_{th}(N+1)L}\right)\right.$$

$$\left.+\sigma\Sigma_D I_\omega \exp\left(\frac{\varphi}{E_{ph}(N+1)L}\right)\right]S^{QWIP}, \qquad (1)$$

Here, e is the electron charge, $p = 1-\alpha^{QWIP}$ and G_{th} are the probability of electron capture into QWs and the rate of electron thermionic emission from QWs at weak electric field, respectively, α^{QWIP} is the efficiency of the electron transport through the QW, σ is the cross section of the electron photoescape from bound states in QWs into continuum states above the inter-QW barriers under middle infrared radiation with photon flux I_ω, Σ_D is the donor sheet concentration in QWs, E_{th} and E_{ph} are the characteristic fields determined by the electric-field dependences of the capture and emission rates in the QWIP active region (with $E_{th} < E_{ph}$), L is the period of QWIP structure, N is the number of QWs, so that the net thickness of the QWIP is $W^{QWIP} = (N+1)L$, and $S^{QWIP} = DH^{QWIP}$ is the QWIP area, D and H^{QWIP} are lateral QWIP sizes.

As the potential of the QWIP collector and the HBT base is equal to φ, the emitter electron and the collector hole currents in the HBT at $|V^{LED} + \varphi| \gg k_BT$ are proportional to

$\exp[e(V^{HBT} - \varphi)/k_BT]$. An equation governing the balance of electrons in the QWIP collector and the HBT base n^+-layer can be presented as:

$$\frac{e}{(1-\alpha^{QWIP})}\left[G_{th}\exp\left(\frac{\varphi}{E_{th}(N+1)L}\right)\right.$$
$$\left.+\sigma\Sigma_D I_\omega \exp\left(\frac{\varphi}{E_{ph}(N+1)L}\right)\right]S^{QWIP}$$
$$= j_s(1-\alpha^{HBT})\exp\left[\frac{e(V^{HBT}-\varphi)}{k_BT}\right]S^{HBT}, \qquad (2)$$

where $S^{HBT} = DH^{HBT}$ is the HBT area, H^{HBT} is the width of the HBT emitter and the base, j_s is the saturation current of the HBT emitter, $\alpha^{HBT} < 1$ is the efficiency of the hole transport through the HBT base (base transfer factor), k_B is the Boltzmann constant, and T is the temperature. In deriving Eq. (2) we have put the injection efficiency of the HBT emitter equal to unity and neglected the electron current injected from the LED into the HBT base. The latter is true if the efficiency of the electron transport through the LED active p$^+-$ layer, α^{LED} is rather small, so that a significant portion of such electrons recombine (primarily due to radiative recombination) in this layer. This condition is discussed in the following.

The HBT collector current (output current) formed by holes injected from the emitter and passed the base is given by

$$J^{HBT} = j_s\alpha^{HBT}\exp\left[\frac{e(V^{HBT}-\varphi)}{k_BT}\right]S^{HBT}. \qquad (3)$$

In dark conditions ($I_\omega = 0$), Eq. (2) yields

$$\frac{e\varphi}{k_BT} = b_{th}\left\{\frac{eV^{HBT}}{k_BT}\right.$$
$$\left.+\ln\left[\frac{j_s(1-\alpha^{QWIP})(1-\alpha^{HBT})S^{HBT}}{eG_{th}S^{QWIP}}\right]\right\}, \qquad (4)$$

where $b_{th} = [1+\theta_{th}/(N+1)]^{-1}$ and $\theta_{th} = k_BT/eE_{th}L$. Substituting $e\varphi/k_BT$ from Eq. (4) into Eq. (3), for most realistic case $b_{th} \simeq 1$ we obtain the following formula for the output dark current:

$$J_{th}^{HBT} \simeq \frac{eG_{th}\,S^{QWIP}}{(1-\alpha^{QWIP})}\frac{\alpha^{HBT}}{(1-\alpha^{HBT})}\exp\left(\frac{V^{HBT}}{V_{th}}\right). \qquad (5)$$

Similarly, from Eqs. (2) and (3), considering that $\theta_{ph} = k_BT/eE_{ph}L \ll (N+1)$, one can obtain the following expressions for the output currents under sufficiently strong middle infrared illumination ($I_\omega \gg G_{th}/\sigma\,\Sigma_D$)

$$J_{ph}^{HBT} \simeq \frac{e\sigma\Sigma_D\,S^{QWIP}}{(1-\alpha^{QWIP})}\frac{\alpha^{HBT}}{(1-\alpha^{HBT})}\exp\left(\frac{V^{HBT}}{V_{ph}}\right)\cdot I_\omega. \qquad (6)$$

Here $V_{th} = (N+1)E_{th}L$ and $V_{ph} = (N+1)E_{ph}L$.

Taking into account photon recycling effect under the condition of nonuniform injection [10], one can use the following formula for the LED external quantum efficiency averaged over its area:

$$\eta^{LED} \propto \frac{T_0(1-\delta)(\eta_{int}^{LED})^2}{(1-\delta\eta_{int}^{LED})^{3/2}}. \qquad (7)$$

Here, T_0 and $(1-\delta)$ are the transmission coefficient of the exit interface and the fraction of photons inside the critical angle cone, η_{int}^{LED} is the LED internal quantum efficiency,

3. Output characteristic

Using Eqs. (6) and (7), we arrive at the following formula for the QWIP-HBT-LED device conversion quantum efficiency, η, determined as the ratio of the output near infrared/visible photon flux to the flux of incident middle infrared radiation:

$$\eta = \eta^{QWIP}\cdot\eta^{HBT}\cdot\eta^{LED}, \qquad (8)$$

where

$$\eta^{QWIP} = \frac{\sigma\Sigma_D}{(1-\alpha^{QWIP})}\exp\left[\frac{V^{HBT}}{(N+1)E_{ph}L}\right], \qquad (9)$$

$$\eta^{HBT} = \frac{\alpha^{HBT}}{(1-\alpha^{HBT})}, \qquad (10)$$

and η^{LED} is given by Eq. (7). Equation (8) shows that due to $\eta^{HBT} \gg 1$ (because $\alpha^{HBT} \leq 1$) the QWIP-HBT-LED device conversion efficiency significantly surpasses that of QWIP-LED up-converters. For a QWIP and an HBT one can assume that $\eta^{QWIP} \simeq 0.05 - 0.1$ and $\eta^{HBT} = 100$. Choosing $T_0 = 0.8$, $\delta = 0.98$, $\eta = 0.95$, $\ae W^{LED} \ll 1$, and $\ae H^{LED} = 1-4$ (æ is the absorption coefficient of the LED active layer), one can find $\eta^{LED} \simeq 0.08 - 0.20$ (this relatively high value is due to photon recycling). After that using Eq. (8), we obtain $\eta \simeq 0.4 - 2.0$.

The assumption that the electron current injected from the LED into the HBT base is negligible compared with the other components made in deriving of Eq. (2), is valid when $\alpha^{LED}J^{LED} \ll (1-\alpha^{HBT})J^{HBT}$. Considering that $\alpha^{HBT}J^{HBT} = (1-\alpha^{LED})J^{LED}$, the latter inequality can be presented as

$$\alpha^{LED} \ll (1-\alpha^{HBT}). \qquad (11)$$

Using the standard formulas for the hole and electron diffusion transport efficiency through the HBT base and the LED active layer, respectively, one can rewrite inequality (11) in the form:

$$W^{LED} \gg 2L_D^{LED} \ln\left(\frac{2L_D^{HBT}}{W^{HBT}}\right), \qquad (12)$$

where L_D^{HBT} and L_D^{LED} are the diffusion lengths of holes and electrons (as minority carriers) in the respective layers. Condition (12) indicates that the electron transport efficiency through the LED active layer must be small, while the hole transport efficiency in the HBT base should not be too close to unity. Hence, as seen from Eq. (12), the thickness of the LED active layer must be sufficiently large, while the thickness of the HBT base can not be too small. These limitations are the consequences of the HBT and LED integration. If condition (11) is not satisfied, the electron injection from the LED into the HBT base creates a positive feedback. This will lead to a marked increase in the both J^{HBT} and J^{LED} even in the absence of infrared illumination, i.e., in a significant thermal (“dark”) output near infrared signal. Once parameter α^{HBT} may not be too small, the HBT amplification is limited. Using Eqs. (11) and (12), one can obtain $\mathcal{K}^{HBT} \leq 1/(1-\alpha^{HBT}) < 1/\alpha^{LED} \simeq 2\exp(-W^{LED}/L_D^{LED})$.

It is expected that imaging devices with the QWIP-HBT-LED pixels under consideration can exhibit noise characteristics similar to those based on QWIP arrays electrically connected with read-out integrated circuits.

4. Conclusion

A novel integrated QWIP-HBT-LED pixel for infrared FPAs was proposed and evaluated using the developed device model. It was shown that the external quantum efficiency of middle-to-near infrared up-conversion can be of the order of unity that can provide significant advantages of QWIP-HBT-LED based FPAs over the FPAs of other types.

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