PERGAMON

Solid-State Electronics 43 (1999) 2201–2207

SOLID-STATE ELECTRONICS

Light-emitting p^+nn^+-heterodiode with additional heterojunction in the n-base

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Received 17 June 1999; accepted 13 July 1999

Abstract

It is shown that a p^+nn^+-heterodiode with an additional nn-heterojunction in the n-base can be a very effective light-emitting phototransistor or transistor. A depletion layer of the new intermediate heterojunction splits the n-base into two new bases: wider bandgap phototransistor (transistor) base 1 and narrower bandgap light-emitter base 2. A coefficient of light-to-light conversion (of an input light absorbed in base 1 into an output light emitted in base 2) can be very high due to very high phototransistor gain. Effects of avalanche multiplication in the depletion layer of the intermediate heterojunction, edge multiplication in an accumulation layer of the same junction and thermionic electron emission across a conduction band discontinuity barrier are taken into account. Various material systems appropriate for implementation of the considered device are discussed.

1. Introduction

The conventional structure of light-emitting pin-heterodiode includes a central narrow-gap light-emitting base (with an active region) and two side wide-gap emitters, that supply the base with holes (p^+-emitter) and electrons (n^+-emitter). Besides the simplest variant of this heterodiode there exist numerous versions with complicated (and sometimes sophisticated) base design. Usually these complications are aimed for special confinement of electrons, holes and radiation to raise efficiency of light emitters, to improve radiation in quality, or to seek certain particularities of light emitters for effective application in optoelectronics. Here we try to consider shortly one of such versions — a p^+nn^+-heterodiode with an additional nn-heterojunction in the base that separates this base into wide-gap and narrow-gap parts. We show that such a heterodiode actually is a light-emitting heterostructure phototransistor (LEHPT). This phototransistor can serve as an effective light-to-light transducer: it can convert an input radiation into more long-wave output radiation with multiplication both of photon number and full intensity of radiation. A variant with a base contact to the wide-gap part of the base (a light emitting heterostructure bipolar transistor: LEHBT) can be an effective light emitter with a speed control of emission by means of small base currents.

2. Heterodiode structure: light-emitting phototransistor regime

We consider the p^+nn^+-heterodiode shown in Fig. 1. It contains three junctions: a left-side p^+n-junction, a right-side nn^+-junction and an additional nn-hetero-

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0038-1101/99/$ - see front matter
PII: S0038-1101(99)00190-2

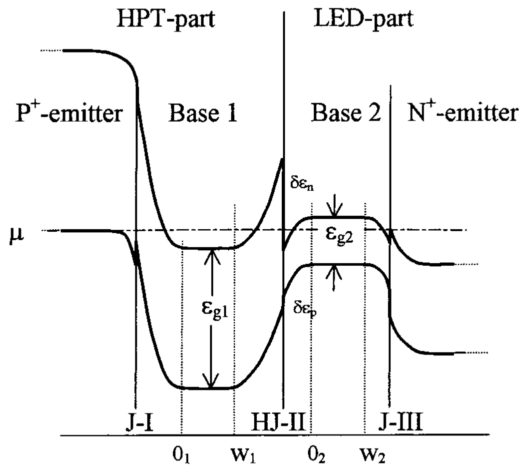

Fig. 1. Equilibrium band diagram of the considered light-emitting heterostructure phototransistor (LEHPT).

junction between them. We number these junctions as junction I (the p^+n-emitter junction; J-I), heterojunction II (the intermediate nn-heterojunction; HJ-II) and junction III (the backside nn^+-emitter; J-III). The side junctions also have to be heterojunctions because their assignments are to provide effective injection of holes from the left and electrons from the right into the complex n-base.

HJ-II separates the considered diode into two parts:

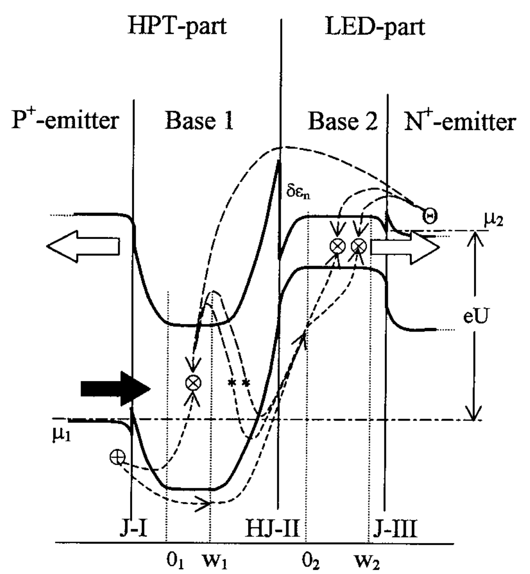

Fig. 2. Band diagram of the LEHPT for a working regime. Designations: ⊕ — hole injection; Θ — electron injection; ⊗ — recombination; * — photogeneration; the filled arrow designates the input radiation, the unfilled arrows designate the light emission.

a left HPT-part (HPT = heterostructure phototransistor) and a right LED-part (LED = light-emitting diode). Each of these parts has own n-base: left base 1 and right base 2. Base 1 is a wide-gap base and holes are injected into this base from the p^+-emitter region through forward-biased J-I (see Fig. 2). These holes have to pass a thin quasineutral base layer with minimum losses and must be extracted from this layer to a depletion layer (DL) of HJ-II, normally reverse-biased. An electrical field in the depletion layer delivers and emits these holes to narrow-gap base 2, where they recombine with electrons emitted from n^+-emitter through right J-III. It is assumed that there is a big difference of bandgaps in bases 1 and 2 ($\varepsilon_{g1} > \varepsilon_{g2}$ with a noticeable reserve) and, as a result, a big asymmetry of discontinuities in electron and valence bands. We assume that HJ-II is of type I and a band offset in the electron band, $\delta\varepsilon_n$ greatly exceeds a band offset in the valence band, $\delta\varepsilon_p$: $\delta\varepsilon_n \approx \delta\varepsilon_g = \varepsilon_{g1}$-$\varepsilon_{g2} \gg \delta\varepsilon_p$. (We will present some examples of such heterostuctures later on). This heterojunction (if both bases are approximately equally donor-doped) forms a power depletion layer, which is spread in base 1. As a result the HPT-part has a transistor structure both formally and in essence. The right LED-part appears instead of a collector p-region and acts as an effective collector region for the HPT-part. This LED-part appears as a light-emitting diode (formally and in reality) if: (1) a radiative recombination prevails over nonradiative forms in base 2 and (2) the HPT-part can appear as a high effective hole emitter. For the latter, the electron current flowing across and through HJ-II from the LED-part to the HPT-part has to be negligible. Just for this purpose, a large discontinuity in the electron band is needed in order to impede a noticeable thermoionic emission of electrons from the right to the left.

When the considered p^+nn^+-diode is forward-biased, a voltage drops mainly across reverse-biased HJ-II. Therefore to reach a significant current density we have to use either (i) photogeneration of electron-hole pairs in the HPT-part (a HPT-regime) or (ii) hole injection from the p^+-emitter due to a base current J_{b1} through a special contact with base 1 (a HBT-regime). At the HPT-regime photons with energy $\hbar\omega_1$, absorbed in the HPT-part, induce emission of photons with energy $\hbar\omega_2$ from the LED-part. We have a light-to-light transducer with a conversion coefficient

$$K = \frac{\phi_2}{\phi_1} = k_1 k_2 \frac{1}{1-\alpha_1}, \qquad (1)$$

where $\phi_{1,2}$ are intensities of input and output light (in photons/cm^2 × s), respectively, α_1 is a current gain of the HPT-part and coefficients $k_{1,2}$ take light and carrier losses in the HPT- and LED-parts into account, respectively (like a passive absorption, a nonradiative recombination, etc.). It is assumed that α_1 is close to 1. An energy conversion coefficient is equal to $K_E = (\omega_2/\omega_1)K$. It is greater than 1 if $1-\alpha_1 < k_1 k_2(\omega_2/\omega_1)$.

3. Current–voltage characteristics for the light-emitting phototransistor regime

If both bases are narrow enough, an applied voltage, U, drops mainly across the three junctions: $U = U_{\rm I}+U_{\rm II}+U_{\rm III}$. To calculate these voltages we assume that hole gases in all parts of the heterodiode are nondegenerate. A hole concentration in base 1 at J-I is equal to $p(0_1) = p_{0_1}\exp\psi_{\rm I}$, where p_{0_1} is an equilibrium hole concentration at the same point, $\psi_{\rm I} = eU_{\rm I}/T$ and T is a temperature in energy units. An analogous expression for J-III is $n(w_2) = n_{0_2}\exp\psi_{\rm III}$, where $n(w_2)$ is an electron concentration in base 2 at J-III, n_{0_2} is its equilibrium value and $\psi_{\rm III} = eU_{\rm III}/T$. For a low injection level in base 2 we have $n(w_2) \cong n_{0_2} \cong N_2$, where N_2 is a donor concentration in base 2 and $\psi_{\rm III} \approx 0$. For a high injection level in base 2 we have $n(w_2) \cong p(w_2)$ and $\psi_{\rm III} \cong \ln(p(w_2)/N_2)$. For HJ-II there is a correlation:

$$\frac{p(w_1)}{p_{0_1}} = \frac{p(0_2)\exp(-\psi_{\rm II})}{p_{0_2}}, \tag{2}$$

which allows us to calculate $\psi_{\rm II}$ via $p(w_1)$ and $p(0_1)$. Here $p(w_1)$ and $p(0_1)$ are hole concentrations in quasineutral regions of bases 1 and 2 on the different sides of heterojunction II, respectively (see Fig. 1); p_{0_1} and p_{0_2} are equilibrium values of these concentrations. As a result, for a small injection level in base 2 we obtain

$$\psi \cong \psi_{\rm I}+\psi_{\rm II} = \ln[p(0_2)p(0_1)/p_{0_2}p(w_1)] \tag{3}$$

and for a high injection level

$$\psi = \psi_{\rm I}+\psi_{\rm II}+\psi_{\rm III} = \ln[p(0_2)p(0_1)p(w_2)/p(w_1)(n_{\rm i2})^2], \tag{4}$$

where $n_{\rm i2}$ is an intrinsic carrier concentration in base 2.

To calculate concentrations $p(0_{1,2})$, $p(w_{1,2})$ we solve diffusion-drift problems in bases 1,2 assuming that only the hole currents flow through junctions J-I and HJ-II and only the electron current flows through J-III. All the currents are initiated by a primary photocurrent j generated in base 1 at $x = w_1$. We obtain:

$$p(0_1)/p_{0_1} = 1+[J+j\alpha_1/(1-\alpha_1)]/J_1;$$

$$p(w_1)/p_{0_1} = 1+[j/(1-\alpha_1)-J]/J_1, \tag{5}$$

where $\alpha_1 = 1/\cosh(\beta_1 w_1)$, $J_1 = \beta_1 D_1 p_{0_1}/\tanh(\beta_1 w_1/2)$, D_1 is a diffusion coefficient of holes in base 1, $\beta_1 = (D_1\tau_1)^{-1/2}$ is their inverse diffusion length, τ_1 is their lifetime and w_1 is a length of a quasineutral region of base 1;

$$p(0_2) = p_{0_2}(1+J/J_2') \tag{6}$$

for a low injection level in base 2 (here $J_2' = \beta_{p_2}D_{p_2}p_{0_2}\tanh(\beta_{p_2}w_{p_2})$, D_{p_2} is a diffusion coefficient of holes in base 2, $\beta_{p_2} = (D_{p_2}\tau_2)^{-1/2}$ is their inverse diffusion length, τ_2 is their lifetime, w_2 is a length of a quasineutral region of base 2) and

$$p(0_2)/p_{0_2} = 1-J[1/(1-\kappa_2)-\gamma_2]/J_2;$$

$$p(w_2)/p_{0_2} = 1+J[\kappa_2/(1-\kappa_2)+\gamma_2]/J_2 \tag{7}$$

for a high injection level in base 2. Here $J_2 = \beta_2 D_2 p_{0_2}/\tanh(\beta_2 w_2/2)$, $D_2 = 2D_{p_2}D_{n_2}/(D_{p_2}+D_{n_2})$ is a bipolar diffusion coefficient in base 2, $\beta_2 = (D_2\tau_2)^{-1/2}$ is an inverse bipolar diffusion length, $\kappa_2 = 1/\cosh(\beta_2 w_2)$ and $\gamma_2 = D_{p_2}/(D_{p_2}+D_{n_2})$, where D_{n2} is an electron diffusion coefficient in base 2.

As a result of substitution of expressions (5) and (6) for $p(0_1)$, $p(w_1)$ and $p(0_2)$ in formula (3) we obtain

$$e^{\psi} \cong \frac{J}{J_2'} \times \frac{J+(j\alpha_1/1-\alpha_1)}{j/(1-\alpha_1)-J}. \tag{8}$$

Formula (8) is justified if $J \gg J_1$, $j\alpha_1/(1-\alpha_1) \gg J_1$ and $\psi \gg 1$. For $J_2' e^{\psi} \ll j\alpha_1/(1-\alpha_1)$ we have $J \cong (J_2'/\alpha_1)e^{\psi}$ and the current is practically independent of the primary photocurrent j. In the opposite case a current is saturated: $J \cong j/(1-\alpha_1)$.

For a high injection level in base 2 we have to use formula (4) instead of (3) and expression (7); then we obtain

$$e^{\psi} \cong \left(\frac{J}{J_{\rm C}}\right)^2 \times \frac{J+j\alpha_1/(1-\alpha_1)}{j/(1-\alpha_1)-J}, \tag{9}$$

where

$$J_{\rm C} = \frac{n_{\rm i2}\beta_2 D_2}{\mathrm{th}(\beta_2 w_2/2)[(\kappa_2/(1-\kappa_2)^2)+\gamma_2(1-\gamma_2)]^{1/2}}. \tag{9a}$$

For $J_{\rm C}e^{\psi/2} \ll j\alpha_1/(1-\alpha_1)$ we have $J \cong (J_{\rm C}e^{\psi/2})/\alpha_1^{1/2}$ as for some equivalent pin-diode. In the opposite case we have $J \cong j/(1-\alpha_1)$ as before. The current saturation means that all of the increase in a voltage drops across HJ-II. This leads to an expansion of the depletion layer into base 1 and shortening the length w_1 of the quasineutral region in this base. This shortening induces raising the current gain of the HPT-part α_1 and increasing both J and ϕ_2 with an increase in U (the Early effect).

We have to note that formulae (8) and (9) are strictly valid if the primary photocurrent j is generated in base 1 just at HJ-II (in the depletion layer or at $x \approx w_I$). However, for the admitted assumption $\alpha_1 \cong 1$ errors in these formulae are minor for arbitrary points of the photogeneration in base 1 (for example, [1]). The photogeneration can be transferred in the p^+-emitter region where a special absorption layer [2,3] for the input radiation can be formed.

4. Multiplication and thermionic emission in heterojunction II

Formulae obtained in the previous section assume that electron currents through HJ-II are absent in full. There are several sources for the existence of these above-neglected currents. First we consider impact ionization of current carriers in high electric field regions around HJ-II. Hot holes drifting through the depletion layer of this heterojunction from the HPT-part to the LED-part ionize electron–hole couples. The electric field in this layer separates the created pairs. Holes drift to the LED-part and electrons drift in the opposite direction. These secondary electrons and holes become hot and able to ionize new pairs of current carriers and we reach the avalanche multiplication. In addition, electrons, which come back in base 1, induce new injection of holes from the p^+-emitter (like the primary photoelectrons). As a result we have to replace the above-obtained current $J = J_0 = j/(1-\alpha_1)$ (for the quasisaturated regime) with a new value

$$J = \frac{jM}{1-\alpha_1 M}, \tag{10}$$

where $M = M(U_{II})$ is an avalanche multiplication coefficient for the depletion layer at HJ-II. This effect is the same as in the ordinary HPT's (see, for example, Ref. [4]). Accordingly we have to replace a factor $1/(1-\alpha_1)$ on the right side of Eq. (1) with a new factor $M/(1-\alpha_1 M)$.

Along with the avalanche multiplication, we take into account another multiplication effect in HJ-II called *edge multiplication*. Hot holes transferring from the depletion layer on the left side of HJ-II to the accumulation layer on the right side of it have a high kinetic energy and are able to ionize electron-hole couples in the narrow-gap semiconductor (Fig. 3). Secondary electrons that are generated as a result of this ionization can not overcome the heterobarrier because a large discontinuity $\delta\varepsilon_n$ is assumed. Therefore they can not induce the avalanche multiplication, but they can raise a concentration of carriers in base 2. This increase in concentration leads to some replacements in formulae (6)–(9). We have to replace J_2' in formulae (6) and (8) with a value $J_2'' = J_2'/M'$ where $M' = M'(U_{II})$ is an edge multiplication coefficient for HJ-II. If $J_2'' e^{\psi} \gg j\alpha_1/(1-\alpha_1)$, current J is saturated ($J \cong j/(1-\alpha_1)$) as above, but a hole concentration in base 2 is multiplied M' times and transformation coefficient K is also gained M' times for the same primary photocurrents.

For a high injection level in base 2 we have to change formulae (7) and to replace the square-bracketing expression in the denominator on the right side of formula (9a) with a new expression:

$$\frac{\kappa_2}{(1-\kappa_2)^2} + \gamma_2(1-\gamma_2) \rightarrow \gamma_2(M'-\gamma_2) + \frac{M'^2\kappa_2}{(1-\kappa_2)^2}.$$

For short bases 2 when $\kappa_2 \cong 1$ we again obtain M'-fold increase in the gain.

Regimes where avalanche multiplication is absent and edge multiplication is present are preferable because (i) they take place at smaller voltages U, and (ii) the gain increases without increasing the current. The edge multiplication coefficient may not be small for narrow-gap bases 2.

Electrons can be emitted from heterojunction II into base 1 not only as a result M-fold avalanche multiplication of hole current flowing from base 1 to base 2. Another mechanism is a direct thermionic emission of electrons across the heterobarrier. Such thermionic electron current j_{th} was considered repeatedly for different material systems, with different approaches to the problem (see, for example, Refs. [5,6,7]). An increase in voltage U_{II} increases current density j_{th} due to both an increase in number of electrons in the accumulation layer and lowering the heterobarrier height for electrons arriving from base 2. This height is equal to $\delta\varepsilon' = \delta\varepsilon_n - eU_{0II}^{(2)} - eU_{II}^{(2)}$ where $eU_{0II}^{(2)}$ is an equilibrium

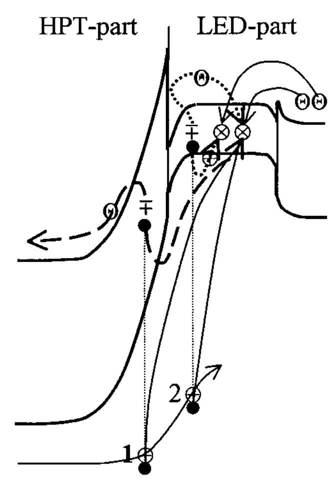

Fig. 3. Two impact processes considered: (1) avalanche multiplication (dashed lines) and (2) edge multiplication (dotted lines). Designation ± marks an impact ionization act. Other designations are the same as in Fig. 2.

depth of the accumulation layer and $U_{II}^{(2)}$ is a part of voltage U_{II} dropped across this layer. An increase in U_{II} increases $eU_{II}^{(2)}$ and decreases $\delta\varepsilon'$. Therefore j_{th} rises with U_{II}.

Since the thermionic electron current is gained in the HPT-part as primary photocurrent j, full current J for the quasisaturated regime can be written in the form:

$$J \cong \frac{j + j_{th}(U_{II})}{1 - \alpha_1(U_{II})}. \tag{11}$$

This additive form of the full current may not be preserved if we take into account effects of the hole current on $j_{th}(U_{II})$. It seems that the strongest of these effects is the heating of electrons of the accumulation layer by hot holes traversed the depletion layer. The effect of edge multiplication induced by these holes was already considered above. The heating of accumulation layer electrons leads to the increase in $j_{th}(U_{II})$, which can be presented in the form:

$$j_{th} = j_{th}^{(0)}(U_{II}) + \alpha_s(U_{II})J_{pII}, \tag{12}$$

where $j_{th}^{(0)}(U_{II})$ is a thermionic electron current without the heating effect, J_{pII} is a hole current at HJ-II and $\alpha_s(U_{II})$ is a certain coefficient that takes the heating effect into consideration. The second component on the right side of formula (12) is an additional thermionic current induced by the heating. As a result we can write the full current J as:

$$J = \frac{j(1 + \alpha_s) + j_{th}^{(0)}}{1 - \alpha_1 - \alpha_1\alpha_s}. \tag{13}$$

Formula (13) shows that the heating effect reminds us of the avalanche multiplication effect (see formula (10)). As a result of the positive feedback both the denominator in formula (13) and the denominator in formula (10) can decrease all the way down to 0. Therefore, to provide a sufficient voltage range for the phototransistor regime it is necessary to diminish M (down to 1) and α_s (down to 0). This requires both a maximum bandgap ε_{g1} and a maximum discontinuity $\delta\varepsilon_n$. At the same time, in order to provide the useful effect of edge multiplication we need to decrease bandgap ε_{g2} and to keep a certain positive discontinuity $\delta\varepsilon_p$ (HJ-II has to be of type I!). However, we have to remember that an excessive decrease in the relation $\varepsilon_{g2}/\varepsilon_{g1}$ diminishes energy transformation coefficient K_E.

For quantitative calculations we need to know the above introduced coefficients $M'(U_{II})$ and $\alpha_s(U_{II})$, but a strict description of these values is outside the framework of this article.

5. Appropriate material systems

It is simpler to meet requirements of the previous sections in the material system AlSb–GaSb–InAs. Since lattice constants of these crystals are noticeably different, detail compositions of isomorphic layers on the basis of the crystals are usually ternary and quaternary alloys that depend on the selected substrate [8]. However, this variety of details can be neglected using a rough schematic approach for qualitative presentations of results and discussions (see, for example, Refs. [9,10,11]). To obtain a maximum conduction band discontinuity $\delta\varepsilon_n$ it is advantageous to select InAs as the material for base 2 and AlSb as the material for base 1. However, firstly, InAs and AlSb form a heterostructure of type II (and we prefer type I) and secondly it is very difficult to select any more wide-bandgap p^+-emitter for AlSb base 1. Therefore we need to choose compound $(AlSb)_{1-x}(GaSb)_x$ for base 1 and compound $(InAs)_{1-y}(GaSb)_y$ for base 2. In this case the p^+-emitter can be selected from AlSb and the backside n^+-emitter can be from the same material as base 1. The estimated values of bandgaps and offsets for $x = 0.5$ and $y = 0.67$ are as follows: $\varepsilon_{g1} \approx 1.4$ eV; $\varepsilon_{g2} \approx 0.6$ eV; $\delta\varepsilon_p \approx 0.08$ eV; $\delta\varepsilon_n \approx 0.7$ eV. For our estimations, we assume that $\delta\varepsilon_p$ in system $Al_{0.5}Ga_{0.5}Sb/GaSb$ is equal to 0.25 eV (for example, Ref. [12]). To obtain a higher barrier $\delta\varepsilon_n$, we can select $x = 0.75$–0.8 and $y = 0.5$. Then $\delta\varepsilon_n$is nearing 0.8 eV.

In the InP–substrate material system we must select heterojunction $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ as HJ-II. Then $\varepsilon_{g2} \approx 0.75$ eV; $\varepsilon_{g1} \approx 1.47$ eV; $\delta\varepsilon_p \approx 0.2$ eV; $\delta\varepsilon_n \approx 0.52$ eV; see Refs. [13,14]. This latter value of $\delta\varepsilon_n$ is still high enough; but a lower value would be undesirable. We can select InP as the material for the backside n^+-emitter, but it is difficult to obtain p^+-emitter that would have a wider bandgap then InAlAs (without mentioning such exotic materials as p^+-$AlAs_{\sim 0.5}Sb_{\sim 0.5}$ or p^+-AlPSb isomorphic with InP). To avoid this difficulty we can complicate the design of the HPT-part, namely we can replace homogeneous base 1 with an inhomogeneous base (Fig. 4).

We assume that base 1 (that is the space between HJ-II and J-I) now consists of a more narrow-bandgap part (the bandgap value is $\varepsilon_{g1} > \varepsilon_{g2}$ as above) and a more wide-gap barrier part (the bandgap value is $\varepsilon_{g12} > \varepsilon_{g1}$). These parts are separated by a new heterojunction. This heterojunction I_1 (HJ-I_1) may not be very sharp (that is it can be a gradient bandgap region as in Fig. 4). The wide-gap barrier part has to be narrower than the depletion layer of HJ-II at $U_{II} > 0$; that is, this layer has to expand into a narrow-gap part of base 1 for the whole phototransistor range of voltages U. In this case we (1) keep a necessary high value of $\delta\varepsilon_n$ and protect the phototransistor regime against excessive thermionic electron emission; (2) keep

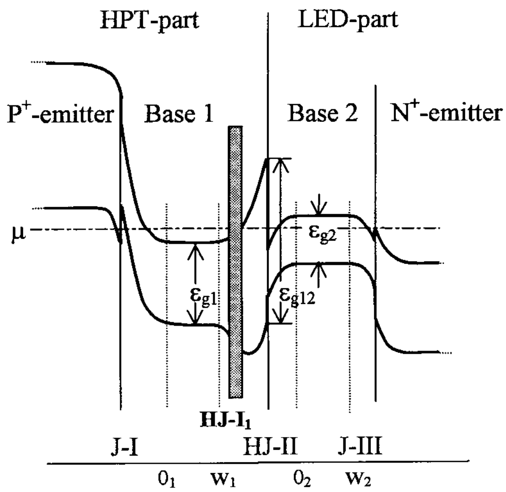

Fig. 4. LEHPT-structure with new heterojunction HJ-I_1 in base 1.

a high enough value of ε_{g12} at the point of maximum electric field and protect the regime against low-voltage avalanche multiplication; (3) decrease relation $\varepsilon_{g1}/\varepsilon_{g2} < \varepsilon_{g12}/\varepsilon_{g2}$ and increase coefficient K_E; (4) can use the high-efficient p^+-emitter with some intermediate bandgap ε_g: $\varepsilon_{g1} < \varepsilon_g \leq \varepsilon_{g12}$. We can keep n-$In_{0.52}Al_{0.48}As$ as the heterobarrier material with a bandgap $\varepsilon_{g12} = 1.47$ eV for HJ-II. As the material for the p^+-emitter $p^+-In_{0.52}Al_{0.48}As$ can be chosen. As the material for the narrow-bandgap part of base1 we can select an intermediate compound In(GaAl)As, isomorphic with InP. For example, compound $In_{0.53}Al_{0.22}Ga_{0.25}As$ has been used as a p-base material for npn-HBT [15]. (We note that alongside numerous works on npn-HBT's in this material system there are a lot of works on pnp-HBT's with $p^+-In_{0.52}Al_{0.48}As$-emitters and n-$In_{0.53}Ga_{0.47}As$-bases: see [16] and references therein).

Finally, we note that the structure of p^+nn^+-LEHPT with the internal heterobarrier in the base shown in Fig.3 reminds us of the structure of a diode light emitter with tunnel barrier. It is described in [17]. However, in our case, we try to organize the LEHPT-regime and limit the electron current flowing through the heterobarrier down to 0. In [17] this barrier is tunnel-penetrable and therefore admits a noticeable electron current.

6. Discussion and conclusion

Above we have assumed that thermionic electron current j_{th} rises in proportion to hole current J_{pII} according to formula (12). However, with increasing J_{pII} this dependence can become superlinear because the denser electron-hole plasma in base 2 takes energy from injected hot holes more effectively (in comparison with other mechanisms of hole energy dissipation). This superlinearity can be presented as increasing with J_{pII} coefficient $\alpha_s(U_{II})$ in formula (12). This results in turn in a decrease in the denominator in formula (13) and in a possible switching to the photothyristor regime: $\alpha_s(U_{II},J_{pII}) \cong (1-\alpha_1)/\alpha_1$. If n^+n-heterojunction III contains a large enough discontinuity in the conduction band, a still more effective photothyristor regime appears as a result of shortening base 2. Then a certain part of hot electrons emitted by this backside junction J-III reaches HJ-II while remaining hot and leaves for base 1. In this case, base II can be characterized by nonzero hot electron transistor gain α_2 and this value has to be subtracted from 1 in the denominator in formula (13). Detailed consideration of the photothyristor regime is outside the framework of this work and will be presented elsewhere.

Speed of the considered LEHPT-regime is determined firstly by a lifetime of nonequilibrium carriers, τ_2, in light-emitting base 2 and secondly by a lifetime of nonequilibrium holes, τ_1, in base 1. This is because the phototransistor regime is equivalent to the common collector transistor regime [18]. Therefore the LEHPT does not yield in speed to the conventional LED-regime only if $\tau_1 < \tau_2$. This requirement demands very rigid conditions for the design of the HPT-part. A hole traversing time across base 1 (including time of drift across the depletion layer) has to be much smaller than τ_1, which has to be smaller than τ_2.

For the LEHBT-regime, when the base current in base 1 controls the light emission, a new additional condition appears: time $\tau_1' = \tau_{RC}/(1-\alpha_1)$ has to be smaller than τ_2 as well [18]. Here τ_{RC} is the charge time of an emitter-base capacity across a base resistance in base 1. If $\tau_1,\tau_1' < \tau_2$, the LEHBT, which is controlled by the small base current of base 1, is the same speed as the LED is. (We have assumed that this LED is fabricated on the basis of the LED-part of our device and controlled by the $(1-\alpha_1)^{-1}$-time greater current).

This effect also takes place in a case where the LED-part contains a Fabry–Perot-cavity and functions as a laser.

In conclusion, we summarize our results. We have suggested the p^+nn^+-structure with an additional nn-heterojunction in the base as an effective light-controlled or base-current–controlled light emitter. The depletion layer of the embedded heterojunction splits the base into two new bases: wider bandgap base 1 and narrower bandgap base 2. The latter is a light-emitter and the former is a current-controller for it. Base1 works as a base of an effective HPT and controls the common current of both bases and the light emission from base 2. If the conditions for the creation of high speed of the HPT-part are completed, we can keep a high speed of radiation modulation for a much smaller modulating power (due to large transistor gain). The LEHBT-regime allows us dual modulation control, which is an additional advantage in comparison with the conventional LED.

Acknowledgements

Authors cordially thank Olga Melnikova for the careful reading of the manuscript. This work has been supported in part by the NSF (grant No. ECS 9523729).

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