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Gain Optimization of $SI_{0.53}GE_{0.47}$ Heterojunction Bipolar Phototransistor

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ABSTRACT:

Demand for high speed opto-electronic integrated circuits has induced the integration of p-i-n photodiode in HBT itself. Combinely the device is called Heterojunction Phototransistor. In this paper $Si_{0.53}Ge_{0.47}$ HPT is considered and gain analysis in terms of photocurrent density is done. Operation of transistor is described. Mathematical derivation of gain formula and subsequent analysis of parameters speak that device under study is capable of detection as well as amplification by β times of the received signal. The use of single HPT to play the dual role will greatly simplify the fabrication of the OEIC receiver in the monolithic form. On the basis of the results it is expected that proposed HPT with derived optimum parameters will emerge as an excellent alternative for high speed wideband optical receivers.

1. INTRODUCTION

In optical communication, receiver designers have employed PIN photodiode as the detector due to its compatibility with that of HBT [1]. However this adds to collector capacitance and series resistance thus degrading the high frequency capabilities of HBT [2]. An alternate to PIN that has not been yet employed extensively, is the bipolar Heterojunction phototransistor HPT. With this, In addition to its epitaxial and fabrication process compatibility with the HBT, the HPT offers the advantage of optical gain which can contribute to improved receiver sensitivity and signal to noise ratio [3].

In this paper the material combination $Si_{0.53}Ge_{0.47}$ is taken as it gives better optical response in 1550 nanometer wavelength region and gain analysis of $Si_{0.53}Ge_{0.47}$ type

HPT is done. The device under consideration has an n-type Si emitter, p-type $Si_{0.53}Ge_{0.47}$ base and n-type $Si_{0.53}Ge_{0.47}$ Collector

N	P	N
n-type Si Emitter	p-type $Si_{0.53}Ge_{0.47}$ Base	n-type $Si_{0.53}Ge_{0.47}$ Collector

Fig1. Scheme of $Si_{0.53}Ge_{0.47}$ HBT

as shown in fig(1). The HBT improves on BJT in terms of speed and frequency [3]. In SiGe graded heterostructure transistors, the amount of germanium in the base is graded, making the band gap narrower at the collector than at the emitter, thus achieving the tapered band gap to improve frequency response [4].

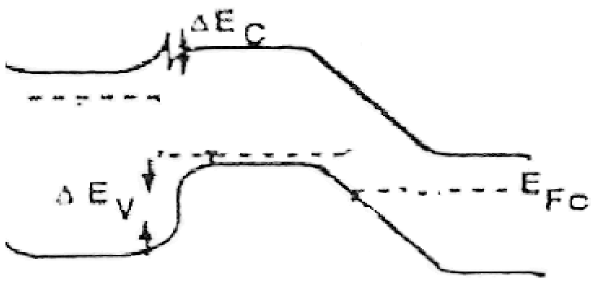


Fig (2) HBT energy band diagram

2. DEVICE CONFIGURATION:

In NPN HBT differing semiconductor materials are used for emitter and base region to create heterojunction. The effect is to limit the injection of holes from the base into the emitter region, because the potential barrier in the valence band is higher than in the conduction band. This allows a high doping density to be used in the base, thus reducing the base resistance while maintaining the gain.

Due to the need to manufacture HBT devices with extremely high doped thin base layers, molecular beam epitaxy is principally employed [5]. In addition to base, emitter and collector layers highly doped layers are deposited on either side of collector and emitter to facilitate an ohmic contact, which are placed on the contact layers after exposure by photolithography and etching [6]. The contact layer underneath the collector named subcollector, is an active part of the transistor. PIN type photo detector is formed by base-collector-subcollector layers.

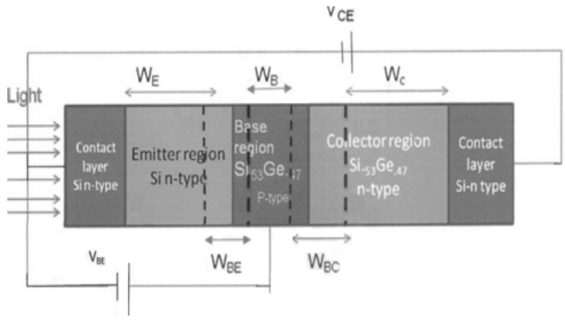


Fig (3) Device Configuration of HPT

3. OPERATION:

The incident optical signal is received by the HPT through the transparent emitter as shown in figure [3] of schematic configuration. The radiation passes through transparent window of emitter and gets absorbed in the base and collector region, creating electron-hole pairs. Thus photo-generated holes accumulate in the base and alter the base emitter potential. This in turn calls for injection of electron from the emitter into the base region to re-establish the charge neutrality in this region. Thus current gain is achieved by normal transistor action, when the base width W_b is less than the diffusion length of the injected electrons L_{nb}. The function of the wide gap emitter is to increase the emitter injection efficiency by preventing reverse injections of holes from the base into the emitter. The carrier injection across the emitter can be written as [7]

$$Y = \frac{I_n}{I_p} \alpha \frac{N_{de}}{N_{db}} \exp\left[\frac{\Delta E_g}{KT}\right] \text{----------} \qquad (1)$$

In this expression, the ratio of electron current I_n to hole current I_p crossing the emitter junction is proportional to the ratio of doping in the emitter N_{de} and the base N_{db}, and varies also exponentially with energy band gap difference ΔE_g between the two semiconductors. Since ΔE_g appears in the exponential factor, even small value can affect the injection efficiency significantly. Now the primary objective in this present work is to compute photo currents and establish the gain formula for the photo transistor in terms of photo current density.

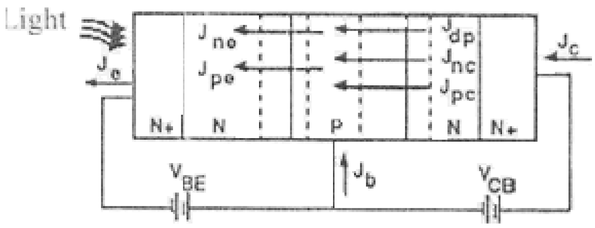


Fig 4-Current components for HPT photo transistor

4. COMPONENTS OF PHOTOCURRENT:

For computation of various components of currents, Let us look at the fig 4. Here optical illumination is through the emitter side. The emitter metal and emitter N^+ contact layers are partially removed to allow light penetration. The effects of optical absorption in the emitter are negligible due to its wide band gap. The optical absorption in the base portion of the emitter-base space charge region is also negligible. Since the base is much more heavily doped than the emitter, the penetration of the space-charge region into the base is very small and much less than the optical absorption length so there is negligible absorption in space charge region.

Optical absorption in the base produces a photo current I_p that contributes to the base current. This photo current density comprises three components.

1. J_{op} = due to optical absorption in the quasi neutral base.
2. J_{dpl} = due to absorption in base collector space charge region within a diffusion length from the edge of the base collector space charge region.
3. J_{pc} = due to absorption in the neutral collector.

Now The total photo current can be expressed as –

$I_{ph} = A_E (J_{ph} + J_{dpl} + J_{op})$,------- (2)

Where

A_E = emitter area, now to find out photo current density J_{ph}, let us define

D_{nb} = the electron diffusion constant

$\tau_n =$ electron minority carrier life time in the base.

V_{jp} = the band bending on the base side of the emitter-base Heterojunction [8]

$V_{jp} = \in \left(V_{bi}^{E} - V_{BE}\right)$---------- (3)

Where

V_{bi}^{E} = built in potential of the emitter base junction

and $\in = \dfrac{\in_E N_{de}}{\in_E N_{de} + \in_B N_{ab}}$ ----------- (4)

where

N_{de} = doping in the emitter

N_{db} = doping in the base

$\alpha_c =$ absorption coefficient in the collector

$\eta_c =$ collector optical quantum efficiency

$W_{BC} =$ width of the collector space charge region.

Generation (g_c) in the collector region [8]

$$g_c = q\eta_c \frac{\alpha_c L_{pc}}{\alpha_e^2 L_{pc}^2 - 1} e^{-\{\alpha_b W_B + \alpha_c W_{BC}\}} \times \left[\alpha_e L_{pc} - \frac{E_{2c}}{E_{1c}} - \frac{L_{pc}}{E_k}\left(\alpha_c - \frac{S_c}{D_{pc}}\right) e^{-\alpha_e W_e}\right] \text{----} \quad (5)$$

Where $E_{1c} = Cosh\left(\dfrac{W_e}{L_{pc}}\right) + \dfrac{L_{pc} S_c}{D_{pe}} Sinh\left(\dfrac{W_e}{L_{pc}}\right)$--------- (6)

$$E_{2c} = Sinh\left(\frac{W_c}{L_{pc}}\right) + \frac{L_{pc} S_c}{D_{pe}} Sinh\left(\frac{W_c}{L_{pc}}\right) \text{---------} \quad (7)$$

Where

S_c = Surface recombination velocity

Photo current density J_{ph} is given by the difference of the collector and emitter currents density as given by

$J_{ph} = (J_c - J_e)_{opt}$--------- (8)

After substituting the values we get the final result for the photo current density

$$J_{ph} = F_o\left[g_c + q\eta_c e^{-\alpha_b W_B}\left(1 - e^{-\alpha_b W_{BC}}\right)\right] + \frac{J_{no} \in_b F_o}{n_o(x_{pe})[\theta_n - \eta_n\phi_n]}$$

$$\times\left(f_{ne}\left\{\eta_n\left[Cosh\left(\frac{W_b}{L_{nb}}\right) - 1\right] - 1\right\} + f_{ne}\left\{\theta_n\left[Cosh\left(\frac{W_B}{L_{nb}}\right) - 1\right] - \phi_n\right\}\right) \text{--} \quad (9)$$

In this equation the first term arises from optical absorption in the neutral collector and diffusion of the photo generated holes to the base collector space charge region where they are swept across by the electric field and collected. Based on the above analysis we can find the optical gain G for the three terminal configuration for the photo transistor in terms of the small signal current gain and photo current density.

$$G = \frac{(\beta + 1)J_{ph}}{qF_o} \text{-----------} \quad (10)$$

5. ANALYSIS:

Looking at equation (10) of small signal current gain and photocurrent density (9) we find that small signal current gain is strong function of the basewidth (w_B). Plotting optical gain G versus W_B (varying from 0 to 0.25 µm)

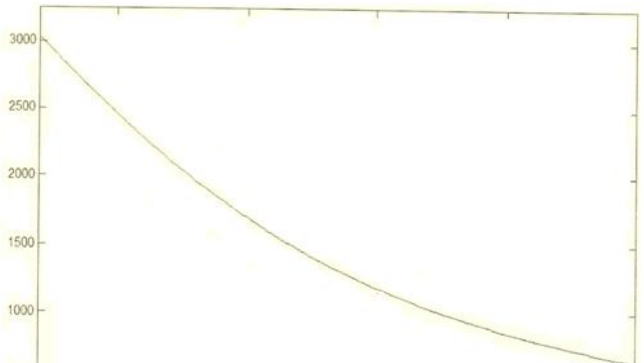


Fig (5): plot of optical gain versus base width

From this plot of fig(5) We find that at every small base width, the small signal current gain is decreasing rapidly keeping the base doping fixed. Overall the small signal current gain reduces with the increase in base width or area. Therefore it is necessary to keep base area or width as small as possible.

Now plotting the optical gain for base doping N_{dB} keeping the base width fixed through equations (10),(9) and (4), we get the following graph

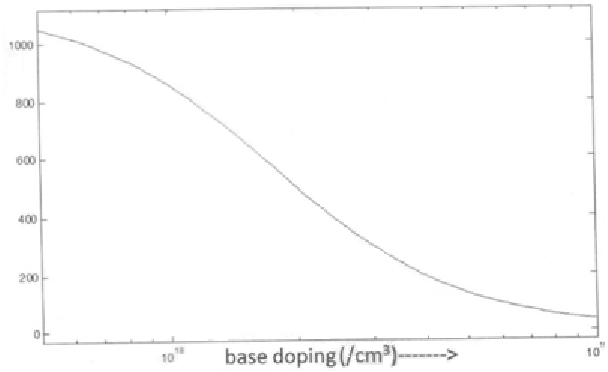
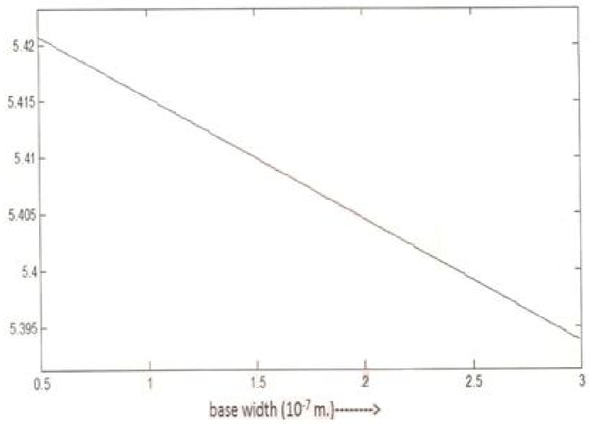


Fig (6): Plot of optical gain versus base doping

From this plot of fig(6) we find that current gain is decreasing rapidly with increase in base doping. Here we must remember that to achieve improved frequency response we should have heavily doped base so as to reduce base resistance. Therefore a tradeoff is needed between base doping and current gain.

Now plotting the photocurrent density versus base width through equation (9) we get the following curve



Fig(7): Photocurrent density versus Base width

From this fig(7) we can observe that photocurrent density decreases with the increase in base width. From fig(6) and (7) we can optimize that while manufacturing $Si_{0.53}Ge_{0.47}$ HPT the base width must be taken as 50nm and base doping as 10^{13} /cm^3 or 10^{19}/m^3 for the optimum performance.

Now plotting equation (9) and (7) for photocurrent density versus collector width w_c keeping collector doping constant, we get following graph

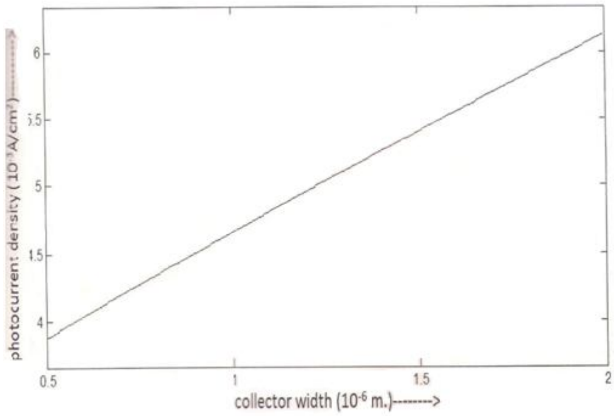
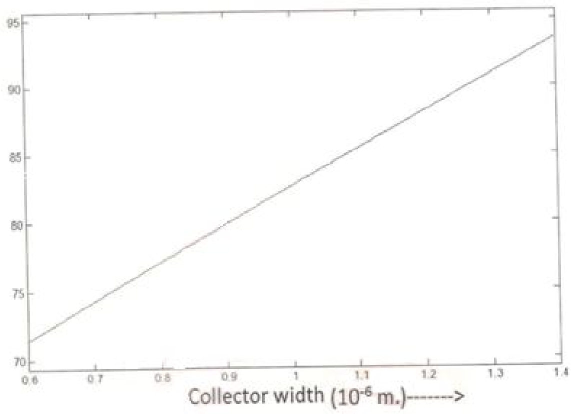


Fig (8): photocurrent density versus collector width

From this fig(8) its evident that as the collector thickness or width increases, the photocurrent density also increases linearly, therefore collector width may be selected near to 2.0 µm.

Now plotting equations (10),(9) and (7) for optical gain versus collector width, we find following curve.



Fig(9):optical gain versus collector width

From fig(9) we find that optical gain increases linearly and for collector layer thickness ≤ 0.7µm the optical gain starts diminishing as if collector is completely depleted, whereas if we increase the collector width, we see that collector component of photocurrent density increases almost linearly. Therefore collector width may be selected as 2.0µm.

6. CONCLUSION:

Proposed Heterojunction phototransistor with optimum parameters has gain equation in which photocurrent density gives the benefit of β times amplification of optical current at the front end of receivers, further heavily doped base and lightly doped emitter reduce the base resistance and junction capacitance which is a necessity for improved frequency response. The discussed configuration of $Si_{0.53}Ge_{0.47}$ HPT has capability to detect as well as amplify the optical signal over a large band of frequencies. The use of a single HPT to play the dual role of detector and amplifier will greatly simplify the fabrication of OEIC receiver in the monolithic form. On the basis of the results it is expected that the proposed HPT with optimum parameters will emerge as an excellent alternative in the future optical communication systems.

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