The Frequency Response of Resonant Cavity Enhanced P-i-N Photodiode

Dušan S. Golubović, Petar S. Matavulj, and Jovan B. Radunović

Department of Microelectronics and Engineering Physics,
Faculty of Electrical Engineering, University of Belgrade
Bulevar revolucije 73, P. O. Box 35-54, 11120 Belgrade, Yugoslavia

Frequency response of homostructure GaAs *resonant cavity enhanced* (RCE) P-i-N photodiode [5] desingned for high speed applications [3] is analyzed. Complete phenomenological model for two valley semiconductor [1, 2] is used in analysis. Stability and convergence of applied numerical algorithm are provided by implementation of conditions described in [1, 2]. As we presume monochromatic and completely coherent incident light, quantum efficiency is given by [4]

$$\eta = (1 - R_1)\frac{(1 - e^{-\alpha d})(1 + R_2 e^{-\alpha d}) + \dfrac{2\sqrt{R_2}\,\alpha}{\beta} e^{-\alpha d}\sin(\beta d)\cos(\beta d + \phi_2)}{1 - 2\sqrt{R_1 R_2} e^{-\alpha d}\cos(2\beta d + \phi_1 + \phi_2) + R_1 R_2 e^{-2\alpha d}} \tag{1}$$

where R_1 and R_2 are power reflectivities, ϕ_1 and ϕ_2 are coresponding phase shifts and together represent resonant cavity parameters wich were constant during the simulations. In our simulations are $R_1 = 0.3$, $R_2 = 0.9$, $\phi_1 = 0$ and $\phi_2 = \pi$. β is propagation constant, d is thickness of absorption i-layer and α is absorption coefficent at applied wavelenght.

Incident light power is $W = 0.007\,pW$ and it was also constant during the simulations. For applied light power, maximal concentration of photogenerated carriers is ten time less then concentration of donor ($\gamma = 0.1$), response is linear [1, 2], so that bandwidth usage for response characterization is justified. The analysis has been carried out for submicron thicknesses of absorption layer, two different active areas ($A = 70\,\mu m^2$ and $A = 700\,\mu m^2$) and different bias voltages ($0\,V \leq V_{cc} \leq 10\,V$).

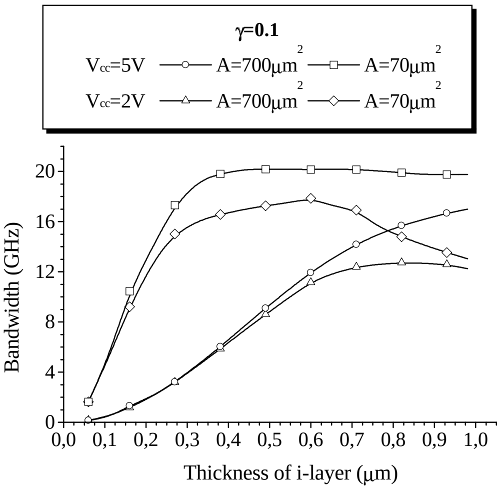

Fig. 1. *The bandwidth versus thickness of i-layer for two different bias voltage $V_{CC} = 5V$ and $V_{CC} = 2V$ and two different values of active area $A = 700\mu m^2$ and $A = 70\mu m^2$.*

Figure 1 shows the dependence of bandwidth on the thickness of absorption layer of RCE P-i-N photodiode. For bias voltage $V_{cc} = 5\,V$ and active area $A = 700\,\mu m^2$ curve increases permanently. According to the results represented in [1] we conclude that bandwidth is limited only by RC-constant for all thicknesses of absorption layer. For the same value of active area and bias voltage $V_{cc} = 2\,V$, the curve has maximum but for higher thicknesses of i-layer. For active area $A = 70\,\mu m^2$ the maximum appears for lower thicknesses of absorption layer and curve decreasing may be observed. In the increasing region of the curve the predominant limiting factor is RC-constant. Appearance of the bandwidth maximum, is predominantly caused by carrier transit time. This is the difference in bandwidth behaviour when compared with conventional P-i-N photodiode in the submicron region [1]. It's easy to notice significant difference in curve slopes for active area $A = 70\,\mu m^2$ in the decreasing region. For $V_{cc} = 5\,V$ beyond maximum the bandwidth slowly decreases. Electrons are localized in the satellite valleys and holes are in saturation owing to high values of the electric field. But, holes are slower and therefore they represent the main limiting factor. For electric field value coresponding to absorption layer thickness $d \approx 0.8\,\mu m$, electron velocity becomes lower than the hole velocity and then electrons, which are not in saturation, start to limit the bandwidth. For bias voltage $V_{cc} = 2\,V$ electrons are localized in the satellite valleys and holes are in saturation. But, electrons are always slower than holes. In this case they predominantly limit the bandwidth and curve decreasing is well observed. In all cases electrons are localized in satellite valleys and nonstationary effects are not noticeable.

Figure 2 shows the dependence of bandwidth on the applied bias voltage of RCE P-i-N photodiode for absorption layer thickness $d = 0.6\,\mu m$. Dash curve represents bandwidth without RC-constant influence

($R = 0\,\Omega$). For bias voltages $V_{cc} \leq 1\,V$ electrons are localized in the central valley where their mobility is much larger than holes mobility. Therefore, banwidth is predominantly limited by holes. For bias voltages $1\,V \leq V_{cc} \leq 2\,V$ intervalley transfer is significant. Owing to intervalley transfer the bandwith increases slower but holes are still the main limiting factor. Maximum corresponds to holes saturation. Beyond maximum the bandwidth increase has much lower slope, because electrons are localized in the satellite valleys where their velocity is small. For $V_{cc} \geq 6\,V$ electron velocity becomes larger then holes saturation velocity and holes influence becomes significant again. Two other curves represent bandwidths when RC-constant influence is present, for two active areas in fact two capacitance values.

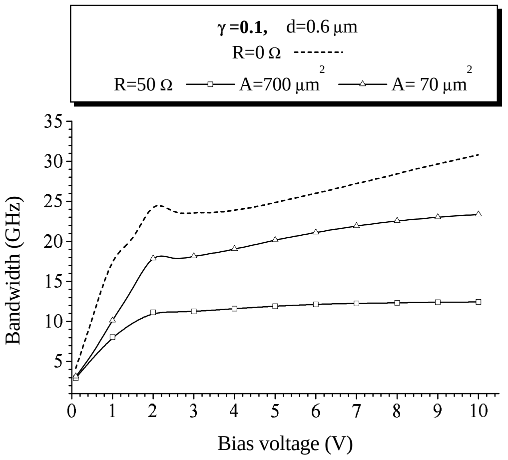

Fig. 2. *The bandwidth versus bias voltage for two different values of load resistance* $R = 0\Omega$ *and* $R = 50\Omega$ *and two different values of active area* $A = 700\mu m^2$ *and* $A = 70\mu m^2$.

We may conclude, in general, that RC-constant presence reduces the bandwidth and decelerates the bandwidth slope vs bias voltage. For active area $A = 70\,\mu m^2$ nonstationary effects, described above, are observed but less than in the case when RC-constant is zero. For active area $A = 700\,\mu m^2$ nonstationary effects, owing to large RC-constant, cannot be observed. Maximum is not present, and curve slope for $V_{cc} \geq 2\,V$ is almost zero. In both cases, for applied bias voltage range, the bandwidth is limited by carrier transit time.

Figures 3a) and 3b) show the dependence of bandwidth-quantum efficiency product on the absorption layer thickness of RCE P-i-N photodiode. Significant difference is observed when compared with conventional P-i-N photodiode [1]. Oscilatory behaviour is a consequence of resonant cavity presence. In case of RCE P-i-N photodiode, it is possible to provide, for special absorption layer thicknesses, very large bandwidth-quantum efficiency product, even 30% larger than in case of conventional P-i-N photodiode (for the same bias voltages and active areas, of course). We may also observe that bandwidth-quantum efficiency product, for special combinations of bias voltages and active areas, has maximum for thicknesses less than $1\,\mu m$. This provides speed increasing without reducing photodiode's gain.

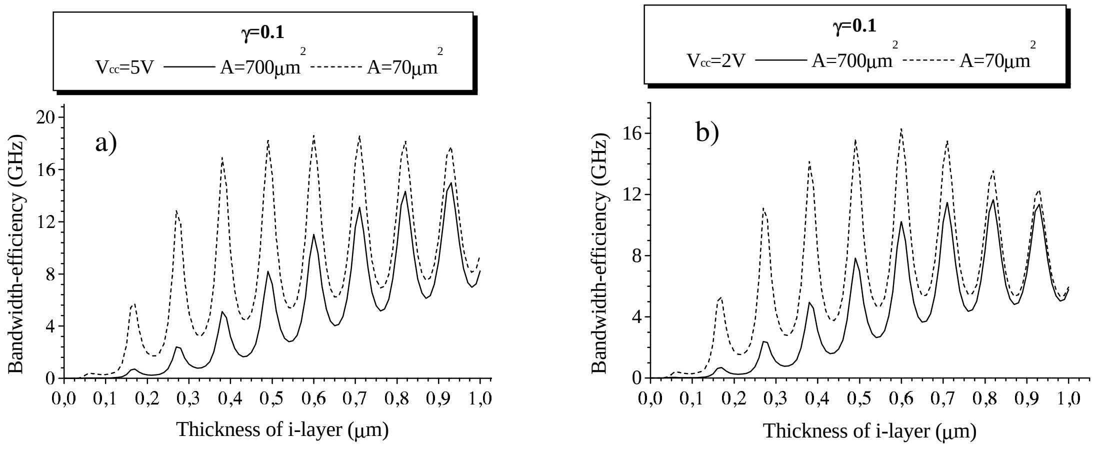

Fig. 3. *The bandwidth-quantum efficiency product versus the i-layer thickness for two different values of active area* $A = 700\mu m^2$ *and* $A = 70\mu m^2$ *and bias voltage a)* $V_{CC} = 5V$ *, b)* $V_{CC} = 2V$.

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