Photoresponse Characteristics from Computationally Efficient Dynamic Model of Uni-traveling Carrier Photodiode

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Abstract— **A time domain model of bulk InGaAs/InP uni-traveling carrier photodiode (UTC-PD) is developed in terms of integral carrier density rate equation. The wavelength dependent responsivity at different absorption width is derived from the model which shows good agreement with the experimental results. The bandwidth of the device is estimated from time dependent photocurrent response.**

Index Terms—Carrier density, Responsivity, Photodiodes

I. INTRODUCTION

Uni-traveling carrier photodiode (UTC-PD) plays an important role in millimeter wave and terahertz generation as its bandwidth has been expanded in that region over ordinary photodiode with innovative ideas [1-2]. The notable research works to model UTC-PD so far mainly adopt frequency domain representation of the device as they are specially interested to derive large bandwidth from the device [1]. However, there is a need for time dependent model. To obtain temporal characteristics and ultrafast response of the device computational efficiency of the model is always a challenge as carrier density is a function of both position and time. The novelty of this work is to elegantly extract the dynamic behavior of the device from the traveling wave model in conjunction with fast computation of parameters due to linearization of absorption coefficient with carrier density. Though the model is primarily meant for time domain analysis, the spatial variation of responsivity against absorption layer width of the device is derived which is shown and verified with the experimental results.

In this work, the bulk material absorption coefficient is modeled as a function of carrier density and wavelength. A comprehensive UTC-PD dynamic traveling wave model is developed from coupled differential equations of incident photon and carrier density rates. Incorporating the effect of self-induced field [2] in UTC-PD, the time dependent photocurrent response of the device is derived from which the bandwidth can be estimated. Finally, few important results are given.

II. THEORY AND MODELING

Schematic of vertically illuminated UTC-PD layer structure is shown in Fig. 1 and its operating principle can be found in [1].

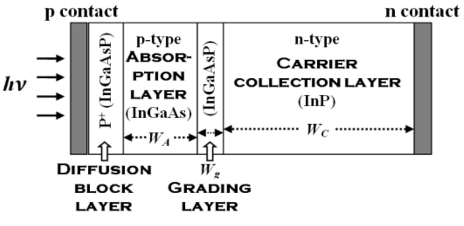

Fig. 1. Schematic layer structure of vertically illuminated UTC-PD

A. *Modeling of Absorption Coefficient*

Responsivity requires accurate calculation of absorption coefficient. Differential equation involving the propagation of incident photon flux Q (photons/sec) and photogenerated carrier density (N) at any specific time t and position x within the absorption layer of UTC-PD, can be written as

$$\frac{dQ(x,t)}{dx} = -[\alpha(N,\lambda) - \beta(N)]Q(x,t) \qquad (1)$$

Where α (m^{-1}) is the bulk material absorption coefficient within the absorption region of direct bandgap InGaAs and β (m^{-1}) is material loss coefficient [3] due to scattering which is a function of carrier density N. $\beta(N)$ can be calculated as $(\beta_0 + \beta_1 N)$ [3] where β_0 and β_1 represent the carrier independent and carrier dependent absorption loss coefficient respectively. Now $\alpha(N,\lambda)$ can be calculated by [4]

$$\alpha(N,\lambda) = \frac{c^2}{4\sqrt{2}\pi^{\frac{3}{2}} n_r^2 \tau \nu^2} \left(\frac{2m_e m_{hh}}{\hbar(m_e+m_{hh})}\right) \sqrt{\nu_0 - \frac{E_g}{h}} \{f_V(E_v)[1 - f_C(E_c)]\} \qquad (2)$$

where ν is the incident optical frequency in UTC-PD and other material parameters of (2) are given in [4]. Here we only consider the transition rate of photogenerated electrons from the valence band (VB) energy level E_v to conduction band (CB) energy level E_c due to optical excitation within the absorption region of UTC-PD. Using the Fermi-Dirac distribution in the VB and CB, we can write

$$f_V(E_v) = \frac{1}{\exp\left(\frac{E_v - E_{fv}}{kT}\right)+1} \text{ and } f_C(E_c) = \frac{1}{\exp\left(\frac{E_c - E_{fc}}{kT}\right)+1} \qquad (3)$$

$$E_v = (h\nu - E_g)\frac{m_e}{(m_e+m_{hh})}, E_c = -(h\nu - E_g)\frac{m_{hh}}{(m_e+m_{hh})} \qquad (4)$$

and E_{fv} and E_{fc} are the quasi Fermi level at the VB and CB relative to the band edges and can be approximated under reverse bias condition as [5]

$$E_{fv} = [\ln v + v\{64 + 0.05524v(64 + \sqrt{v})\}^{-\frac{1}{4}}]kT$$
$$E_{fc} = -\ [\ln u + u\{64 + 0.05524u(64 + \sqrt{u})\}^{-\frac{1}{4}}]kT \qquad (5)$$

where, $v = \frac{N}{N_v}$, $u = \frac{N}{N_c}$ and N_v and N_c are the constant terms can be given as

$$N_v = 2\left(\frac{m_{dh}kT}{2\pi\hbar^2}\right)^{\frac{3}{2}};\ N_c = 2\left(\frac{m_e kT}{2\pi\hbar^2}\right)^{\frac{3}{2}} \qquad (6)$$

B. *Extraction of Absorption Parameters*

From (2) to (6) the material absorption coefficient $\alpha(N,\lambda)$ is obtained. In general $\alpha(N,\lambda)$ is non-linear with respect to N and it's plot against N is shown by the dotted line in Fig. 2(a). The plot of absorption coefficient $\alpha(N,\lambda)$ can be linearly approximated by $m(N - N_0)$ as shown by solid line in Fig. 2(a), where m is the slope of the line and N_0 is the linear fit parameter denoting carrier density at transparency. These values will be used subsequently in

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(10). If N_{max} and N_{min} are the two extreme carrier densities of interest in the linear region and α_{max} and α_{min} are the corresponding material absorption coefficients then m and N_0 can be calculated as follows:

$$m = \frac{\alpha_{max}-\alpha_{min}}{N_{max}-N_{min}} \quad \text{and} \quad N_0 = -\frac{\alpha_{max}}{m} + N_{max} \qquad (7)$$

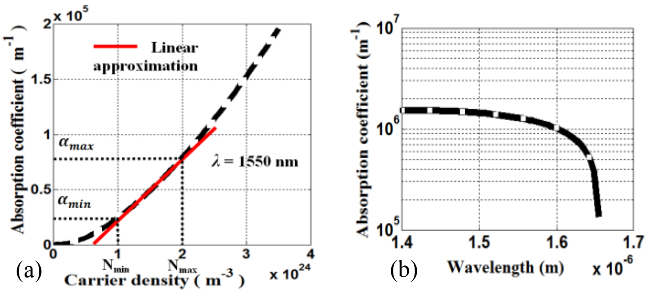

Fig. 2. The material absorption coefficient $\alpha(N,\lambda)$ versus (a) carrier density [$N(x,t)$] and (b) wavelength (λ)

The plot of absorption coefficient versus wavelength is shown in Fig. 2(b).

C. Time dependent Model

The carrier density (N) rate equation within the absorption region of UTC-PD can be written as [6]

$$\frac{dN(x,t)}{dt} = -\frac{[\alpha(N,\lambda)-\beta(N)]Q(x,t)}{A} - \frac{N(x,t)}{\tau} + \frac{\partial}{\partial x}[\mu_n N(x,t) E_{ind}(x)] \qquad (8)$$

where τ is the carrier recombination lifetime, μ_n is the mobility of electrons in InGaAs and A is the cross-sectional area of the device. The first term in the right hand side of (8) provide the rate of carrier generation from the incident photon flux i.e. $\frac{dQ(x,t)}{volume}$. The negative sign is due to decrease in photon density with excess electron hole pair. The second term is the carrier recombination rate which varies linearly with carrier density and the third term represents photogenerated carriers under drift motion [1] and $E_{ind}(x)$ is the self induced electric field in UTC-PD [2].

Equation (8) is difficult to solve because N is a function of two independent variables x and t. Since we are interested in the dynamic behavior involving time t we can assume a new variable $r(t)$ which is related to $N(x,t)$ by

$$r(t) = A\int_0^{W_A} N(x,t)dx \qquad (9)$$

$r(t)$ denotes integral carrier density over the entire volume within the absorption region. Hence absorption region volume becomes a point source of carrier density. Integrating both side of (8) with respect to x and using (9) and (1) we arrive at the following simple equation

$$\frac{dr(t)}{dt} = Q_{in}(t)[\, e^{-[(m-k_1)\frac{r(t)}{A} - (mN_0+k_0)W_A]} - 1] - \frac{r(t)}{\tau} + \mu_n r(t)\frac{\partial}{\partial x}E_{ind}(x) \qquad (10)$$

The computational complexity in solving (10) has been reduced significantly due to its dependency on single variable t. Solving (10) the time varying photogenerated excess carriers $r(t)$ is obtained. The output photocurrent $i(t)$ which is defined as the total charge per carrier travel time through the photodiode can be calculated from $r(t)$ as

$$i(t) = \frac{qr(t)}{(\tau_A+\tau_g+\tau_C)} \qquad (11)$$

where τ_A [1], τ_g and τ_C [1] are respectively the absorption, grading and collection layer traveling time.

III. RESULTS AND DISCUSSIONS

The device parameter values used in the dynamic model of UTC-PD are given in [3]. The steady state solution of (10) for each wavelength from 1400 nm to 1600 nm gives the responsivity (R) for that wavelength. R can be obtained by dividing (11) with input optical power. For each λ, the value of m and N_0 is obtained from the linearization curve of Fig. 2(a). Fig. 3(a) shows the plot of responsivity with absorption layer width (W_A) which is verified with the experimental results [7]. Fig. 3(b) is the plot of bias dependent responsivity of UTC-PD with wavelength at an input optical power 0 dBm. Fig. 4(a) shows pulse response obtained from the developed model for a super-Gaussian (m=8) optical input pulse of width 1 ps. Slow decay (2 ps) at the output signifies that UTC-PD has a limited modulation bandwidth (~ 300 GHz) which is obtained after carrying out Fourier Transform of the output pulse. The result is shown in Fig. 4(b).

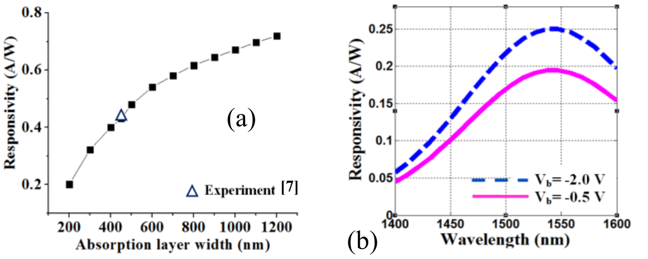

Fig. 3. Responsivity of UTC-PD (a) with W_A and (b) with wavelength at different applied bias (V$_b$)

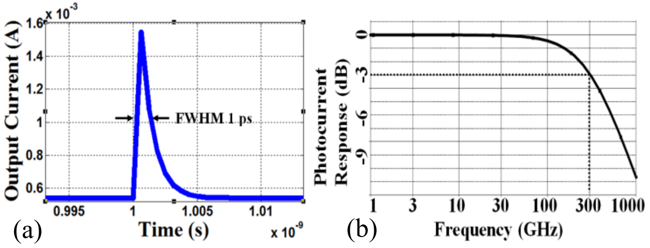

Fig. 4(a). Output photocurrent response of UTC-PD with an input optical pulse and (b) bandwidth of the device

REFERENCES

[1] H. Ito, S. Kodama, Y. Muramoto, T. Furuta, T. Nagatsuma, and T. Ishibashi, “High-speed and high-output InP–InGaAs uni-traveling carrier photodiodes,” *IEEE J. Quantum Electron.*, vol. 10, no. 4, pp. 709–727, Jul./Aug. 2004.

[2] S. Khanra and A. Das Barman, “Circuit Model of UTC-PD with High Power and Enhanced Bandwidth Technique,” *Optical and Quantum Electronics*, Spinger, Dec. 2014; DOI 10.1007/s11082-014-0094-x.

[3] Y. Suematsu and A. R. Adams, *Handbook of Semiconductor Lasers and Photonic Integrated Circuits*, London, U.K.: Chapman & Hall, 1994.

[4] M. J. Connelly, *Semiconductor optical amplifiers,* Boston: Kluwer Academic, 2002, pp. 45-71.

[5] N. G. Nilsson, “Empirical approximations for the Fermi energy of a semiconductor with parabolic bands,” *Appl. Phys. Lett.*, vol. 33, no. 7, pp. 653–654, Oct. 1978.

[6] P. D. Coleman, R. C. Eden, and J. N. Weaver, “Mixing and detection of coherent light in a bulk photoconductor,” *IEEE Transaction on Electron Devices,* pp. 488–497, Nov. 1964.

[7] M. Chtioui, A. Enard, D. Carpentier, S. Bernard, B. Rousseau, F. Lelarge, F. Pommereau, and M. Achouche, “High-power high-linearity uni-traveling-carrier photodiodes for analog photonic links,” *IEEE Photonics Technology Letters,* vol. 20, no. 3, pp. 202–204, Feb. 2008.