Ensemble Monte Carlo Particle Modeling of InGaAs/InP Uni-Traveling-Carrier Photodiodes

M. Ryzhii and V. Ryzhii
Computer Solid State Physics Laboratory
University of Aizu, Aizu-Wakamatsu 965-8580, Japan
E-mail: m-ryzhii@u-aizu.ac.jp

Abstract

An ensemble Monte Carlo particle model for uni-traveling-carrier (UTC) photodiodes is developed. This model is used to study electron and hole nonequilibrium phenomena and transient response of UTC photodiodes.

1 Introduction

A novel heterostructure optoelectronic device - the uni-traveling-carrier (UTC) photodiode proposed and studied by Ishibashi et al. (1997) and Shimizu et al. (1998) - combines ultra-fast operation and high power output. Such a photodiode includes a doped narrow-gap absorption region (p^+–InGaAs) and an undoped or lightly doped wide-gap collector region (N^-–InP). To eliminate the effect of the spike in the conduction band at the InGaAs/InP heterointerface preventing the electron escape from the absorption region into the collector region, a thin heavily doped cliff layer is inserted near the heterojunction. This structure is sandwiched between P^+- and N^+- layers serving as the contacts. The band structure of a UTC photodiode is shown in Fig. 1.

In this communication, we report the study of the response of InGaAs/InP UTC photodiodes to optical pulses with different energies generating electrons and holes in the absorption region. For this purpose we use an ensemble Monte Carlo (MC) particle technique similar to that used previously for the studies of the transient processes in bipolar heterostructure transistors and quantum well infrared photodetectors (M. Ryzhii 1997, M. Ryzhii and V. Ryzhii 2000) and adjusted to the structural features of UTC photodiodes. Our simulator takes into account the band structures of InGaAs and InP layers, the mechanisms of the electron and hole scattering including carrier-carrier interactions, and the self-consistent electric field in the diode active region (between the contacts).

2 Model

The parameters of materials of the UTC photodiode structure used in the MC calculations were extracted from the book by Adachi (1992). The model implemented neglects the influence of a narrow spike formed in the conduction band at the heterojunction on the electron transport due to relatively high tunnel transparency of this spike. For the MC simulations, ensembles of up to 5×10^5 particles (electrons and holes) were protracted. The time-step and the mesh size correspond to 10 fs and 2 nm, respectively. The structural parameters of

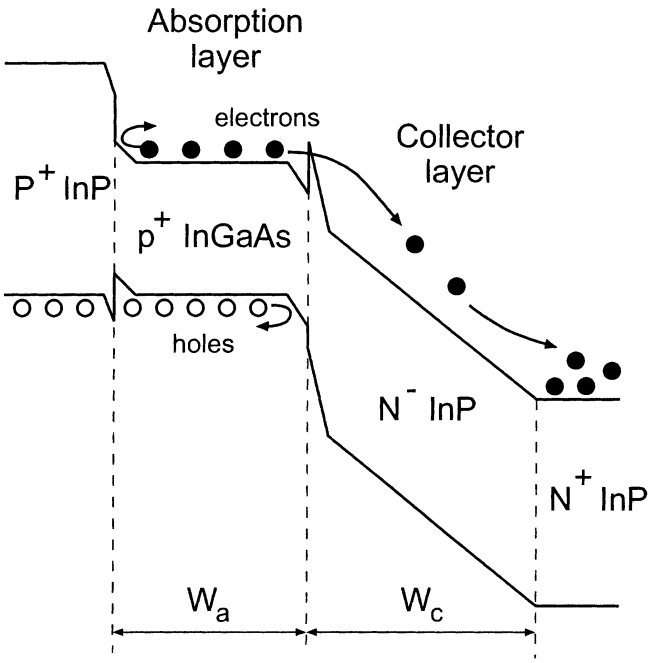

Fig. 1. Schematic view of the UTC photodiode band diagram.

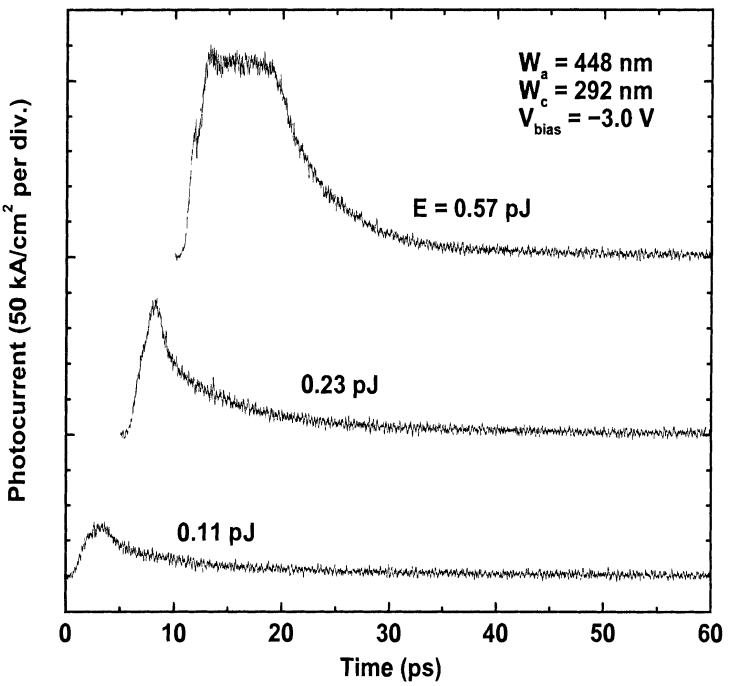

Fig. 2. Transient photocurrent for different absorbed optical energies.

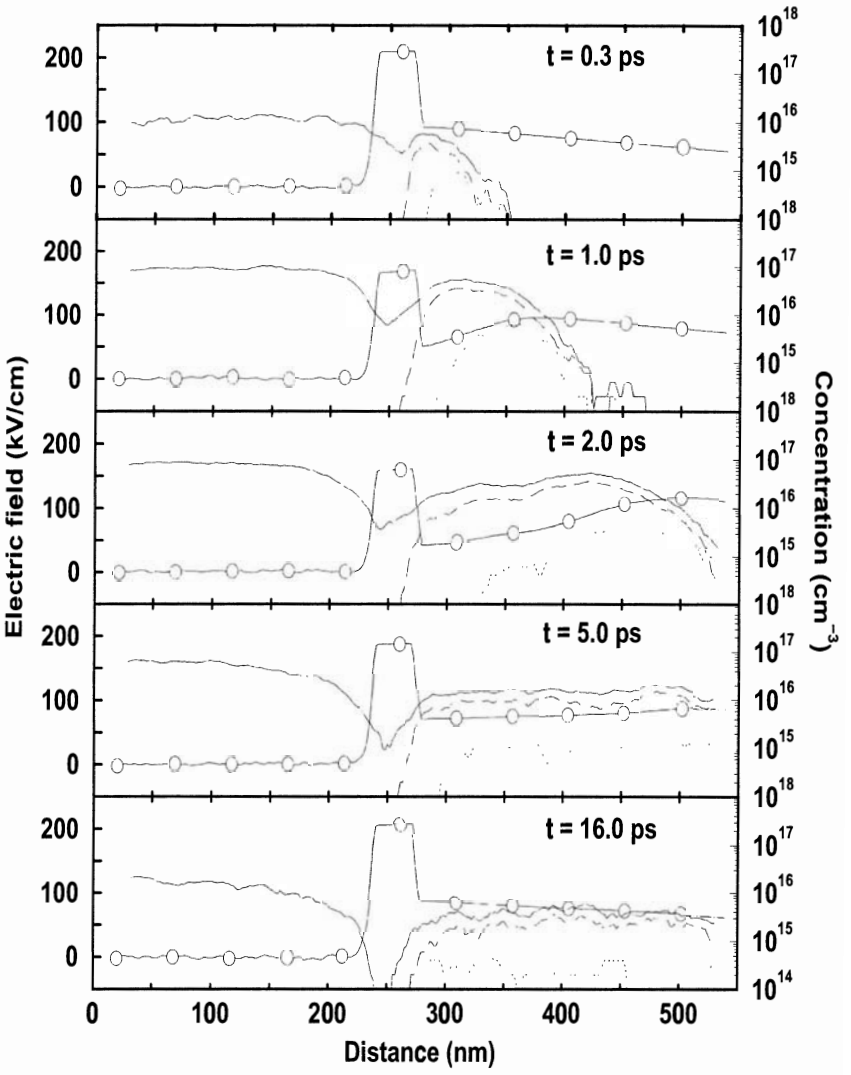

Fig. 3. Snapshots of electric-field (circles) and electron concentration spatial distributions. Solid line corresponds to net electron concentration, dashed line - L-electron concentration, and dotted line - X-electron concentration.

UTC photodiodes used in the simulations were assumed to be similar to that in the experimental studies, namely, the thicknesses of the absorption and collector layers $W_a = 228 - 888$ nm and $W_c = 292$ nm, respectively, the acceptor concentration in the main part of the absorption layer (except a thin undoped spacer adjacent to the heterojunction) $N_a = (0.25 - 1.0) \times 10^{18}$ cm^{-3}, and the device area $A = 20$ μm^2.

3 Results

Using the developed model, we calculated the spatio-temporal distributions of the electric field and carrier concentrations and the transient photocurrent induced in the external circuit. The obtained temporal dependences of the photocurrent were used to calculate the UTC photodiode responsivity as a function of signal frequency.

Figure 2 shows the temporal dependences of photocurrents in a UTC photodiode with $W_a = 448$ nm, and $W_c = 292$ nm at $V_{bias} = -3.0$ V in response to optical pulses ($\lambda = 1.55$ μm) having the Gaussian shape (with FWHM of 1000 fs) and different energies. As seen from Fig. 2, the height of the photocurrent peak increases with increasing absorbed optical energy E while the width of this peak varies insignificantly. At higher optical energies, the photocurrent saturates (so that its top becomes nearly flat) and the duration of the photocurrent pulses substantially rises. This is due to an essential limitation of the current extracted from the absorption region caused by the electron space charge in the collector region. This effect and its details are in agreement with experimental data.

Figure 3 shows the spatial distributions of the electric-field and electron concentration (both in the absorption and collector layers) at different moments for a UTC photodiode with $W_a = 228$ nm, and $W_c = 292$ nm exposed to an optical pulse with FWHM of 390 fs at $V_{bias} = -2.0$ V.

The authors are thankful to Dr. T Ishibashi for valuable discussions.

References

[1] Adachi S. Physical Properties of III-V Semiconductor Compounds: InP, InAs, GaAs, GaP, InGaAs, and InGaAsP. John Wiley & Sons, New York, 1992

[2] Ishibashi T, Kodama S, Shimizu N, Furuta T. High-speed response of uni-traveling-carrier photodiodes. Jpn. J. Appl. Phys. 1997; 36:6263-6268

[3] Ryzhii M. Monte Carlo modeling of transient effects in resonant-tunneling bipolar transistors. Jpn. J. Appl. Phys. 1997; 36:5060-5062

[4] Ryzhii M, Ryzhii V. Monte Carlo modeling of transient recharging processes in quantum-well infrared photodetectors. IEEE Trans. Electron Devices 2000; 47:1935-1942

[5] Shimizu N, Watanabe N, Furuta T, Ishibashi T. Improved response of uni-traveling-carrier photodiodes by carrier injection. Jpn. J. Appl. Phys. 1998; 37:1424-1426