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Design of broadband and high-output power uni-traveling-carrier photodiodes

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ABSTRACT

In this paper, the bandwidth and saturation current of uni-traveling-carrier photodiode (UTC-PD) is investigated by using physics-based modeling. To further improve the performance, novel device structures are proposed. On the one hand, graded bandgap structure is employed in the absorption layer. It is shown that similar to the effect of graded doping method, the electric field in the absorption layer is increased, and thus the bandwidth is improved. Moreover, both the graded doping and graded bandgap structure are optimized. It is found that for the considered UTC-PD, combining use of the optimized graded doping and graded bandgap structure in the absorption layer leads to an improvement of 39.4% in bandwidth. On the other hand, linear doping profile and Gaussian doping profile are proposed to be used in the collection layer. It is shown that the distribution of electric field in the depletion region is improved, which leads to better saturation performance. For the considered UTC-PD, by using the optimized linear doping profile and the Gaussian doping profile, the improvement in saturation current is 18.7% and 25.8%, respectively.

1. Introduction

In recent years, research of exploring broadband and high-efficiency fiber–optic communication systems and wireless communications as well as the other applications has been increasing. Photodiodes (PDs), which can be used to convert optical signal to electrical signal, serve as a key component in those applications. They can be employed in a digital optical front end to provide a distortion-free electrical output signal [1], and also can be used to generate millimeter and sub-millimeter waves for RF transmitters [2]. For many applications, PDs with broadband and high-output RF power are desired. Among various types of PDs, uni-traveling-carrier photodiode (UTC-PD) is very attractive for future fiber–optic systems and the other applications, since it has exhibited excellent high-speed and high-power performance.

UTC-PD has several advantages over the conventional PIN-PD. Firstly for the UTC-PD, the light absorption layer and the depleted collection layer are separated. Since they are independent of each other, the trade-off between the carrier transit time and the RC-time constant for bandwidth limitation is eliminated. In addition, due to this separated structure, the role of holes as the active carriers is eliminated, and only the transportation of the photo-generated high speed electrons determines the device performance. Thus, the limitations caused by the low speed holes turn into the limitations caused by the high speed electrons. This is an essential difference from the conventional PIN-PD. Therefore, the bandwidth and saturation performance of UTC-PD is better than that of PIN-PD.

In the past decade, UTC-PD has been intensively studied [3–23]. In terms of enhancing bandwidth and saturation performance, various designs have been proposed and demonstrated. On the one hand, it has been experimentally demonstrated that the bandwidth performance of UTC-PD can be improved by using an appropriate doping profile in the absorption layer, since the introduced built-in electric field in the absorption layer can help electrons transport more rapidly into the collector. For example, the UTC-PD reported in [17], a step doping profile was adopted in the absorption layer. Similarly, a large slope of linearly graded doping profile was used in the absorption layer of the UTC-PD reported by Shi et al., which can construct a built-in electric field from 2.1 kV/cm to 84 kV/cm [18]. On the other hand, it is found that the output saturation of PDs is mainly caused by the space-charge effect at high current level. And this effect can be reduced by using a technique of charge compensation in the collection layer. As reported in [14], a non-uniformly doped collector was designed to relax the space-charge effect.

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The main focus of this work is to design novel absorption layer and collection layer structures to further improve the bandwidth and saturation performance. As reported in our previous work [23] and some other publications [15,24], the performance of the UTC-PD can be investigated by using the physics-based modeling. The advantage of the physics-based simulation method is that the device can be studied in details without costly experiments as long as appropriate physical models are incorporated. The conventional drift-diffusion model is the simplest charge transport model. It is useful for most of the common devices. However, as the sizes of the devices become smaller, this drift-diffusion approximation is less accurate, since it neglects non-local effects such as velocity overshoot. The electron velocity plays a significant role in determining the performance of UTC-PD. In addition, electron velocity overshoot has been observed experimentally in UTC-PDs [6]. Therefore, in order to ensure the accuracy of the simulation for the studied UTC-PD, the hot carrier transport model is employed in this work. In the following, the epitaxial layers of our considered UTC-PD will be described in details. Then, a short description of hot carrier transport model is followed. Finally, based on the modeling results, novel absorption layer and collection layer structures are developed. It will be shown that by using our proposed absorption layer and collection layer structures, the bandwidth and saturation current can be improved effectively.

2. Physical modeling

2.1. Device under study

In this study, a typical UTC-PD device structure, which is reported by Ishibashi et al. [16], will be considered. The epitaxial layers are shown in Table 1. The topmost layer is the p-type InGaAs contact layer. The anode metal will be deposited on this layer. In order to form a good ohmic contact, this p-type contact layer is heavily doped. Next is the wide bandgap p-type InGaAsP blocking layer. Since the energy gap of this blocking layer is 0.85 eV, and the energy gap of the following p-type InGaAs absorption layer is 0.737 eV, a conduction band offset ΔE_c is formed at the blocking layer and absorption layer interface, which serves as a diffusion barrier for the electrons in the absorption layer. Thus, the role of the blocking layer is to promote the electrons generated in the absorption layer to move towards the InP collection layer and to prevent the diffusion of the electrons to the anode, while the holes are allowed to pass through. Followed is a typical uniformly doped p-type InGaAs absorption layer. It is highly doped to $1\times10^{18}\,\mathrm{cm}^{-3}$ and the thickness is 220 nm. Since the device is operated at the optical wavelength of around 1.55 µm, which is equivalent to photon energy of 0.82 eV, the energy gap of this absorption layer is designed to be 0.737 eV to ensure the electrons that can be excited from the valence band to the conduction band. Relatively, in order to avoid optical absorption, an n-type InP layer, which has a wide energy gap of 1.35 eV, is adopted as the collection layer. And this collection layer is uniformly doped to $1\times10^{16}\,\mathrm{cm}^{-3}$ for charge compensation. Moreover, the doping concentration is very low to ensure the collector that can be completely depleted at normal device operation bias. Since there is an abrupt conduction band barrier at the InGaAs and InP heterojunction interface, which may block the electrons and lead to degradation of the sensitivity and photocurrent, undoped InGaAs, InGaAsP and InP space layers are employed to form a smooth connection between the absorption layer and collection layer. The energy gap of the inserted InGaAsP space layer is 1.0 eV. Additionally, an n-type thin InP cliff layer is added between the undoped InP spacer layer and the lightly doped InP collection layer. This cliff layer, which is highly doped to $1\times10^{18}\,\mathrm{cm}^{-3}$, is used to enhance the electric field near the input side of collection layer. Finally, similar to the p-type contact layer, the cathode metal is connected to the n-type InP subcollection layer, which is heavily doped to reduce the contact resistance.

Table 1
Epitaxial layers of the UTC-PD reported in [16].

Layer	Thickness (nm)	Doping (cm^{-3})/type	Band gap E_g (eV)
p++InGaAs contact	50	3×10^{19}/P	0.737
p++InGaAsP blocking	20	2×10^{19}/P	0.85
p+ InGaAs absorption	220	1×10^{18}/P	0.737
i-InGaAs space	8	–	0.737
i-InGaAsP space	16	–	1.0
i-InP space	6	–	1.35
n+ InP cliff	7	1×10^{18}/N	1.35
n- InP collection	263	1×10^{16}/N	1.35
n+ InP subcollection-2	50	5×10^{18}/N	1.35
n+ InGaAs etch stop	10	1.5×10^{19}/N	0.737
n+ InP subcolleciton-1	500	1.5×10^{19}/N	1.35
i-InGaAs etch stop	10	–	0.737

2.2. Carrier transport models

The carrier transport models, or the current density equations, are usually obtained by applying approximations and simplifications to the Boltzmann transport equation [25]. As mentioned above, in order to ensure the accuracy of the simulation of the studied UTC-PD, the non-local model of carrier transport is required. A commercial physics-based device simulator ATLAS, from Silvaco International, is used in this work. According to the ATLAS, for the simulation of submicron UTC-PD, the energy-balance transport model should be employed. This model follows the derivation by Stratton [26, 27], and it uses a higher order approximation to the Boltzmann transport equation. Compared with the conventional drift-diffusion model, the energy-balance transport model introduces new independent variables for electron and hole temperatures, adds continuity equations for the carrier temperatures, and treats the carrier mobility as functions of the carrier temperatures rather than functions of the local electric field. The energy balance equations are given by [25]

$$\nabla\cdot S_n = \frac{1}{q}J_n\cdot E - W_n - \frac{3k}{2}\frac{\partial}{\partial t}(\lambda_n^{*} n T_n) \tag{1}$$

$$\nabla\cdot S_p = \frac{1}{q}J_p\cdot E - W_p - \frac{3k}{2}\frac{\partial}{\partial t}(\lambda_p^{*} p T_p) \tag{2}$$

in which J_n and J_p are the current densities, S_n and S_p are the energy flux densities from the carrier to the lattice. They can be expressed as [25]

$$J_n = qD_n\nabla n - q\mu_n n\nabla\psi + qnD_n^T\nabla T_n \tag{3}$$

$$J_p = -qD_p\nabla p - q\mu_p p\nabla\psi - qpD_p^T\nabla T_p \tag{4}$$

$$S_n = -K_n\nabla T_n - \left(\frac{k\delta_n}{q}\right)J_n T_n \tag{5}$$

$$S_p = -K_p\nabla T_p - \left(\frac{k\delta_p}{q}\right)J_p T_p \tag{6}$$

where T_n and T_p are the temperature of electrons and holes, W_n and W_p are the energy density loss rates for electrons and holes, D_n and D_p are the thermal diffusivities for electrons and holes, and K_n and K_p are the thermal conductivities of electrons and holes. For