PDL Optimization in Waveguide MQW pin Photodiodes

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Abstract—**In this paper, a simulation model is presented for optimizing the polarization dependent loss (PDL) of waveguide multiple-quantum well (MQW) pin photodiodes (PD). The model accounts for strain, carrier transit time through the MQW layers and free carrier density in the quantum wells.**

Keywords—multiple-quantum well; pin photodiode; simulation model; exciton; polarization dependent loss;

I. Introduction

Photodiodes (PDs) are a key component in optical receivers. Depending on their unique properties, PDs are widely used in various analog and digital applications. Moreover, PDs with large PDL can be used for detecting polarization multiplexed optical signals. These polarization multiplexed optical signals are approved in today's long-haul optical communication links. Waveguide multiple-quantum well (MQW) PDs can provide a large PDL [1-2]. The PDL of MQW PDs can be further tuned by the strain in the MQWs.

In [3] a model to design waveguide MQW pin PDs with zero strain considering the carrier transit time and the free carrier density in the MQWs was proposed. In this paper, the model of [3] is extended by strain in order to introduce an additional parameter for optimizing the PDL of MQW waveguide pin PDs.

II. Theoretical Model

To design MQW pin PDs, there are several issues such as carrier transit time and carrier density that have to be considered. Large carrier transit time lowers the internal quantum efficiency, while large carrier density decreases the saturation light intensity. Both effects lower the responsivity and reduce the bandwidth of MQW pin PD. Considering both effects, we proposed a theoretical model for MQW pin PDs in [3].

However, the model of [3] did not account for strain effects in MQW pin PDs. The strain in MQW affects the performance of MQW devices, since strain has an influence on the band structure.

The strain can be expressed as

$$\begin{aligned} \varepsilon_{//} &= \varepsilon_{xx} = \varepsilon_{yy} = \frac{a_0 - a}{a} \\ \varepsilon_{\perp} &= \varepsilon_{zz} = -2\frac{C_{12}}{C_{11}}\varepsilon_{//} \end{aligned} \qquad (1),$$

where $\varepsilon_{//}$ and $\varepsilon_{\perp}$ are the strain in the plane of the epitaxial growth and in the perpendicular direction, respectively, a is the lattice constant of the absorption layer, and a_0 is the lattice constant of the substrate which in this work is InP. C_{11} and C_{12} are the elastic stiffness constants [4].

Because of the strains, the conduction band and valence bands for light-hole (lh) and heavy-hole (hh) are shifted by the energy

$$\begin{aligned} \Delta E_c &= 2a_c(1-\frac{C_{12}}{C_{11}})\varepsilon_{//} \\ \Delta E_{hh} &= 2a_v(1-\frac{C_{12}}{C_{11}})\varepsilon_{//} + b(1+2\frac{C_{12}}{C_{11}})\varepsilon_{//} \\ \Delta E_{lh} &= 2a_v(1-\frac{C_{12}}{C_{11}})\varepsilon_{//} - b(1+2\frac{C_{12}}{C_{11}})\varepsilon_{//} \end{aligned} \qquad (2),$$

where ΔE_c , ΔE_{hh} and ΔE_{lh} are the shift energy of the conduction band, heavy-hole valence band and light-hole valence band, respectively. a_c and a_v are the conduction band and valence band hydrostatic deformation potentials, and b is the valence band shear deformation potential [4].

Thus, considering the strain in MQW structures, the bandgap in the model of [3] is modified:

$$\begin{aligned} E_{e-hh}(x,y) &= E_g(x,y) + \Delta E_c(x,y) - \Delta E_{hh}(x,y) \\ E_{e-lh}(x,y) &= E_g(x,y) + \Delta E_c(x,y) - \Delta E_{lh}(x,y) \end{aligned} \qquad (3).$$

Here E_{e-hh}, E_{e-lh} and E_g are the bandgap between electron and heavy-hole, the bandgap between electron and light-hole and the material bandgap, respectively. As discussed in [1], the separation of the heavy-hole band and light-hole band in quantum wells results in different absorptions of the transverse electric (TE) polarized light and the transverse magnetic (TM) polarized light. The TE absorption can be assigned to heavy-hole to conduction band (hh-e) and light-hole to conduction band (lh-e) transitions. However, TM absorption appears only

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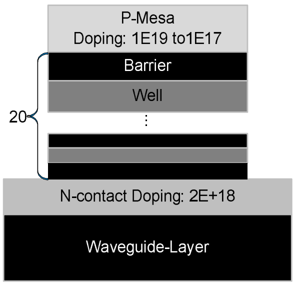

Fig. 1. Diagram of the cross section of the MQW pin PD mesa; the intrinsic absorption layer consists of 20 quantum well layers

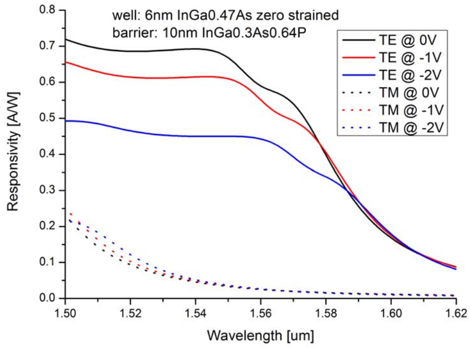

Fig. 2. Simulated responsivity spectra of zero strained MQW pin PD design with reverse voltage ranging from 0V to -2V, for TE and TM polarized input light.

for (lh-e) transitions. Thus, by tuning the strain in a MQW structure of a waveguide photodiode, the PDL can be further optimized. For example, by introducing compressive strain in the wells of an InGaAsP/InP MQW structure, the PD will prefer to absorb TE polarized light.

III. Simulation Results

Two MQW pin PDs one with and the other one without strain were designed. The diagram of Fig. 1 depicts the cross section of a designed waveguide integrated MQW pin PDs from the top to the bottom: the p-mesa with heavy p-doping, the intrinsic MQW absorption layer, the n-mesa with heavy n-doping, and the waveguide layer at the bottom. For the PD without strain the absorption region consists of 20, 6nm thick $InGa_{0.47}As$ quantum wells separated by 10nm thick $InGa_{0.3}As_{0.64}P$ barriers. For the strained PD the absorption region consists of 20, 5nm thick $InGa_{0.45}As$ quantum wells separated by 10nm thick $InGa_{0.3}As_{0.64}P$ barriers causing a compressive strained of 0.14%. The responsivity and the PDL spectra are simulated using the presented model. The parameters used for the simulation were taken from [3] and [4].

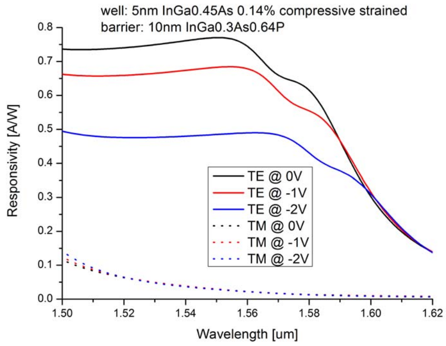

Fig. 3. Simulated responsivity spectra of 0.14% compressive strained MQW pin PD design with reverse voltage ranging from 0V to -2V, for TE and TM polarized input light.

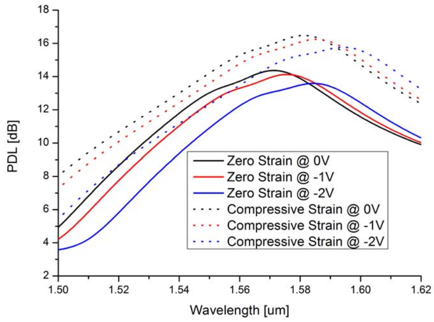

Fig. 4. Simulated PDL spectra of zero strained (solid curves) and 0.14% compressive strained (dotted curves) MQW pin PD design with reverse voltage ranging from 0V to -2V.

The calculated carrier transit for both designs is below 100ps, and the saturation light intensity is larger than $6000kW/cm^2$. Hence, both designs do not suffer from saturation for a input light power below 10mW. Moreover, for simplicity the internal efficiency equals one. Fig. 2 and Fig. 3 show the responsivity spectra of the zero strained design and the compressive strained design. The waveguide PD with compressive strain enhances the TE absorption and simultaneously weakens the TM absorption. Thus, the waveguide PD with compressive strained MQWs has a larger PDL (Fig. 4).

IV. Conclusion

To optimize the PDL of waveguide MQW pin PD a simulation model accounting for strain in MQWs layers is presented. Simulations were carried out to compare designs of MQW pin PDs with and without strains. The simulation results showed that the MQW pin PD with compressive strain have a larger PDL. It is important to include strain into such simulations, because strain affects the band structure and changes the performance of MQW pin PDs.

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