Research Article

Contribution of Series Resistance in Modelling of High-Temperature Type II Superlattice p-i-n Photodiodes

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We analyze some of the consequences of omitting series resistance in InAs/GaSb p-i-n T2SL photodiode dark current modelling, using simplified p-n junction model. Our considerations are limited to generation-recombination and diffusion-effective carrier lifetimes to show the possible scale of over- or underestimating photodiodes parameters in high-temperature region. As is shown, incorrect series resistance value might cause discrepancies in τ_{gr} and τ_{diff} 's estimations over one order of magnitude.

1. Introduction

Type II superlattices (T2SLs), especially InAs/GaSb, are very promising materials for both uncooled as well as cooled mid-wavelength infrared (MWIR) and long wavelength infrared (LWIR) photodetectors [1]. Relative easiness of controlling band offset causes them to be used in different types of structures [2]. Especially, introducing unipolar barriers in various designs based on type II SLs drastically changed the architecture of infrared detectors. At present, the InAs/GaSb T2SLs are considered to be an alternative to the HgCdTe IR material systems [1] and a candidate for the third-generation IR detectors [3]. However, InAs/GaSb T2SL is in an early stage of development. Problems exist in material growth, processing, substrate preparation, and device passivation [4–6]. Moreover, correct interpretations of measured detector characteristics are often difficult due to fact that T2SLs' band structures are much more complicated than bulk materials [7]. From this reason, there have been developed many simplified models [8–13], which assume that T2SL electrical parameters are mainly dependent on energy difference between first conduction and heavy hole miniband (which is treated as an effective bandgap). For an approximative describing of the detector transport mechanisms, the well-known standard theory of p-n junction is used [2, 14]. Recently published results of our group show that usage of this method can give very good fitting between theoretical

predictions and experimental data in a wide range of bias voltage (from -1.6 to $+0.3$ V) and temperature (from 77 to 240 K) for p-i-n and nBn devices [15–17]. It appears that good agreement between both types of results is possible if the influence of series resistance (R_{series}) is taken into consideration, what might be essential in a thermoelectrically cooled (TE) photodetectors (in temperature range above 180 K).

In this paper we present the consequences of R_{series} omitting in the dark current modelling of p-i-n T2SL junctions, often met in literature. These consequences are shown on an example of temperature dependence of two fitting parameters—generation-recombination (τ_{gr}) and diffusion (τ_{diff})-effective carrier lifetimes. Both two mechanisms have decisive influence on current-voltage characteristics of TE-cooled p-i-n T2SL junctions in near-zero bias voltages [17].

2. Experimental Results

In the studies we have chosen representative sample of 10/10 ML InAs/GaSb T2SL in a p-i-n structure, fabricated in the Center for High Technology Materials, University of New Mexico, Albuquerque, NM, USA. The photodiode cutoff wavelength is roughly equal to $5.6\ \mu\text{m}$ at 120 K and $6.2\ \mu\text{m}$ at 230 K [18]. The detector architecture design and measurement details of current-voltage characteristics of

FIGURE 1: Experimental dark current density-voltage characteristics of p-i-n T2SL photodiode at different temperatures (after [17]).

these samples were presented elsewhere [16, 17]. Here we present only a few of the results (see Figures 1 and 2), indispensable for presenting the main goal of the paper.

3. Modelling of Current-Voltage Characteristics

In order to explain current-voltage characteristics of the MWIR type-II SLS photodiodes a bulk-based model with an effective band gap of SL material is used. It is well recognized that the photodiode dark current can be found as a superposition of several mechanisms (see Figure 3):

$$I_{\text{dark}} = I_{\text{diff}} + I_{\text{gr}} + I_{\text{bth}} + I_{\text{tat}} + I_{\text{Rshunt}}, \quad (1)$$

including four main mechanisms: diffusion (I_{diff}), generation-recombination (I_{gr}), band-to-band tunnelling (I_{bth}), and trap-assisted tunnelling (I_{tat}). The remaining mechanism is current due to the shunt resistance (I_{Rshunt} , originates from the surface and bulk leakage current and shows the presence in the reverse bias region).

The relation between the applied voltage, V , and the diffusion current density, J_{diff} , is given by

$$J_{\text{diff}} = J_s \left[\exp\left(\frac{qV}{kT}\right) - 1 \right], \quad (2)$$

where q is the electron charge, k is the Boltzmann's constant, and T is the absolute temperature. In the case of our devices, due to a gradient doping profile at the contacts, we apply the reflective contact configuration, and then the saturation current density J_s can be expressed as

$$J_s = qn_i^2 \left(\frac{D_e}{N_a L_e} \tanh \frac{x_p}{L_e} + \frac{D_h}{N_d L_h} \tanh \frac{x_n}{L_h} \right), \quad (3)$$

FIGURE 2: Experimental resistance-area product versus bias voltage of p-i-n T2SL photodiode at different temperatures (after [17]).

where n_i is the intrinsic carrier concentration, $N_{a,d}$ is acceptor/donor doping concentrations, $\mu_{e,h}$ is minority electron/hole mobility, and $x_{n,p}$ is the device thicknesses (x_n is the thickness of n -type region, instead x_p is the thickness of p -type region). Additionally, $L_{e,h}$ means electron/hole diffusion current length, and $D_{e,h}$ diffusivity (with diffusion lifetime $\tau_{e,h}$), where

$$D_{e,h} = \frac{kT}{q} \mu_{e,h}, \quad L_{e,h} = \sqrt{D_{e,h} \tau_{e,h}}. \quad (4)$$

The g-r current density under reverse-bias voltage and for forward-bias voltage values, that are less than V_b by several kT/q , is derived as

$$J_{\text{gr}} = \frac{qn_i w}{(\tau_{e0} \tau_{h0})^{1/2}} \frac{2 \sinh(qV/2kT)}{q(V_b - V)/kT} f(b), \quad (5)$$

where τ_{e0} and τ_{h0} are the carrier lifetimes for electrons and holes within the depletion region (w is the depletion width). In our estimation we also assumed that $\tau_{e0} = \tau_{h0} = \tau_{\text{gr}}$ and $\tau_e = \tau_h = \tau_{\text{diff}}$. The function $f(b)$ is a complicated expression involving a trap level and an applied voltage [2]. The values of parameters used in a device modelling are taken from published literature [19–21] and are gathered in Table 1 [16].

The description of other mechanisms, essential in high reverse bias voltage condition and detailed discussion of fitting procedure (including simple method of avoiding difficulties connected with the influence of series resistance), can be found in [16].

4. Results and Discussions

In some of the recently published papers related to high operating temperature (HOT) T2SL devices (see, e.g., Cervera et al. [12]) is mentioned the difficulties connected with

TABLE 1: Parameters taken in modelling of MWIR InAs/GaSb superlattice photodiodes.

Device geometry	
thickness of p -type region, x_p	$0.27 \mu\text{m}$
thickness of n -type region, x_n	$2.25 \mu\text{m}$
electrical area	$2.03 \times 10^{-3} \text{ cm}^2$
Donor concentration, N_d	$1 \times 10^{16} \text{ cm}^{-3}$
Acceptor concentration, N_a	$1 \times 10^{18} \text{ cm}^{-3}$
Trap concentration, N_T	$8 \times 10^{14} \text{ cm}^{-3}$
Minority electron mobility, μ_e	$10000 \text{ cm}^2/\text{Vs}$
Minority hole mobility, μ_h	$1000 \text{ cm}^2/\text{Vs}$
Electron-effective mass, m_e^*	$0.015m_0$
Hole effective mass, m_h^*	$0.4m_0$

FIGURE 3: Possible currents operating in the photodiode. I_{diff} is ideal diffusion current, I_{ph} is the photocurrent, I_{gr} is due to a generation-recombination mechanism, I_{tbt} is due to a band-to-band tunnelling, I_{tat} is due to a trap-to-band tunnelling, and R_{shunt} is due to a surface and bulk leakage shunt resistance. Limiting currents act in opposition to diffusion current.

fitting procedure between measured I - V characteristics and theoretical predicted results above 200 K. In our opinion these difficulties are strictly connected with the influence of series resistance in high-temperature region. Because R_{series} -value is connected in a series to all generation-recombination mechanisms (see Figure 3), we should solve the nonlinear problem to obtain voltage drops on both whole device except series resistance and a series resistance separately (see discussion in [16]). Omitting this problem causes it to be impossible to fit to measured dynamic resistance-voltage characteristics, $R_d(V)$, under HOT conditions. It is caused by the fact that voltage drop on device except R_{series} might be essentially lower than measured voltage, what causes considerable changes in shapes of RA -product curves (see Figure 4), and, in consequence, great difficulties in theoretical fitting procedure to the experimental $R_d(V)$ characteristics.

At the beginning, we present a comparison of two simulation results, which were made using the same input parameters, except R_{series} . As we can see on Figure 4, the difference in a bias-dependent peak positions of dynamic resistance is nearly equal to 0.1 V, what in consequence causes significance discrepancy in an effective lifetimes estimations from (2) and (5).

FIGURE 4: The comparison of two simulation results at 230 K, assuming the same input parameters except R_{series} . Curves with 2-index are calculated assuming zero value of R_{series} . Plots with no additional indexes are calculated assuming that $R_{\text{series}} \approx 2 \Omega$ obtained from the fitting to the measured dynamic resistance (see Figure 2) under the forward bias voltage condition (at $\approx 0.2 \text{ V}$).

Second aspect, previously mentioned, is the fact that influences of R_{series} on shapes of different dark current components are effective if the R_{series} value is comparable with dynamic resistance contributions of respective dark current components. This is especially visible for g-r mechanism. As a result, estimating of τ_{gr} and τ_{diff} data assuming incorrect R_{series} value causes significant over- or underestimation in the effective current lifetimes.

Assuming the consideration above, we should underline that it is impossible to fit to measured $RA(V)$ characteristics using (2) and (5), and omitting R_{series} . It causes many researchers to try to fit roughly only to the I - V characteristics, without analysing first derivative of it ($RA(V)$ dependence). In a consequence, for avoiding overestimation of dark current in a near zero-bias voltage region, it is needed to increase τ_{diff} and decrease τ_{gr} at bias voltage about -0.2 V in our case (this value depends on sample, temperature, and R_{series}) shown in Figure 5. Curves with no additional index are calculated using parameters obtained from the correct fitting, but with zero value of R_{series} . Plots with 2 indexes are calculated using incorrect procedure.

As we can see on Figure 6, discrepancies between fitting results, made with and without including R_{series} , increase with temperature. It is caused by the fact that ideal photodiode resistance of p-i-n T2SL photodiode (with $R_{\text{series}} = 0$) decreases with temperature and becomes comparable with weak temperature-dependent series resistance at high-temperature operation. In a consequence, a voltage drop

FIGURE 5: Explanation of incorrect fitting procedure (for more details—see text). Arrows show tendencies in change components of dark current to obtain good fitting to experimental data.

FIGURE 6: Comparison of g-r and diff. effective current lifetimes estimated theoretically for two cases: with including R_{series} and without it (see additional description in the text).

on an ideal diode and on series resistance are comparable, and I - V characteristics essentially change their shapes. This results in under- or overestimations in key photodiode fitting parameters, like τ_{gr} or τ_{diff} . Our results for the MWIR photodiode seem to be confirmed by more direct measurements [22], where effective current lifetimes are weekly temperature dependent over 200 K.

5. Conclusions

In this paper we analyze some of the consequences of omitting series resistance in InAs/GaSb p-i-n T2SL photodiode dark current modelling, using simplified p-n junction model. Our considerations are limited to generation-recombination and diffusion-effective carrier lifetimes to show the possible scale of over- or underestimating photodiodes parameters. As is shown, incorrect series resistance value might cause discrepancies between τ_{gr} and τ_{diff} over one order of magnitude. Our results seem to be good explanation of difficulties in the estimation of parameters of MWIR T2SL photodiodes operated in high-temperature region.

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