Low dark current InGaAs/InAlAs/InP avalanche photodiode

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Abstract. The performance of uncooled InGaAs/InAlAs/InP avalanche photodiodes operating near 1.5 µm has been studied theoretically. Device modelling based on advanced drift and diffusion model with commercial software, the Crosslight APSYS, has been performed. Separate absorption, grading, charge and multiplication avalanche photodiodes with a relatively thick undepleted p-type InGaAs absorption region and thin InAlAs multiplication layer have been considered. Basic physical quantities like band diagram, optical absorption and generation have been calculated. Performance characteristics such as dark- and photo-current, photo-responsivity, multiplication gain, breakdown voltage, excess noise, frequency response and bandwidth have been simulated. Device design optimisation issues have been discussed with respect to the applicable features of the Crosslight APSYS within the framework of drift-diffusion theory. The modelling results are selectively presented and analysed. Simulations of avalanche photodiode structures enable one to increase the device quantum efficiency, reduce the dark current and eliminate impact ionization processes within absorbing layer.

1. Introduction

Avalanche photodiodes (APDs) provide increased sensitivity as compared to conventional p-i-n photodiodes due to the enhancement of the detected signal by internal gain. However, avalanche gain by electron-hole pair production in APDs at high electric fields is inevitably a subject to multiplication noise, restricting the device performance and maximum gain.

High-speed, high-sensitivity, avalanche photodiodes operating at 1.5 µm spectral range are widely utilized in modern high-bit rate and long-haul optical communication systems, particle detection, confocal microscopy, astronomical observations, optical range finding, ultra-sensitive fluorescence and many other applications. High gain-bandwidth product, reduced dark current and low excess noise often characterize these devices. Initial development of these devices was driven by fibre optic telecommunications. Compared to receivers with p-i-n photodiodes, those that utilize APDs achieve better sensitivity of 5-10 dB. Related research was focused on reducing the noise and developing detectors with high gain and high gain-bandwidth products [1,2]. Recently, imaging applications have stimulated development of other type of APDs. For these devices speed is not any further critical. Instead, very low current densities and low multiplication noise are the main requirement [3,4].

Despite of the significant amount of experimental efforts in the developments of photodetectors, better modelling techniques simulating performance of devices are highly demanded. This is particularly indispensable for APDs because of the internal gain due to the impact ionization mechanism. The stochastic character of impact ionization is often taken into account. Modelling based
on statistic approaches have been explored to study the time domain/frequency responses of APD [5-7].

Simulation techniques based on the drift-diffusion model, to study DC characteristics have also been explored [8,9]. Recently, extensive modelling based on dynamic drift-diffusion simulations using Crosslight’s APSYS program, has been performed on conventional InP/InGaAs separate absorption, grading, charge and multiplication (SAGCM) APD structures [10,11].

2. APSYS software

The Crosslight APSYS is a general-purpose 2D/3D finite element analysis and modelling software program for semiconductor devices [12]. It solves Poisson’s equation (1) and the current continuity equations (2), (3) for electrons and holes:

\[
-\nabla \left( \frac{\varepsilon_0 e_{dc}}{q} \nabla V \right) = -n + p + N_D (1 - f_D) - N_A f_A + \sum_j N_f (f_j - f_0)
\]

\[
\nabla \cdot J_n - \sum_j R_{nj} - R_{sp} - R_{st} - R_{au} + G_{opt} \left( \frac{\partial n}{\partial t} + N_D \frac{\partial f_D}{\partial t} \right) = 0
\]

\[
\nabla \cdot J_p + \sum_j R_{pj} + R_{sp} + R_{st} + R_{au} - G_{opt} \left( \frac{\partial p}{\partial t} + N_A \frac{\partial f_A}{\partial t} \right) = 0
\]

where: \( V \) - the electrical potential, \( \varepsilon_{dc} \) - the relative DC dielectric constant, \( n \) - the electron concentration, \( p \) - the hole concentration, \( N_D \) - the shallow donor density, \( N_A \) - the shallow acceptor density, \( f_D \) - the occupancy of the donor level, \( f_A \) - the occupancy of the acceptor level, \( J_n \) and \( J_p \) - electron and hole current, respectively. \( R_{nj} \) and \( R_{pj} \) - electron and hole recombination rates per unit volume through the \( j \)th deep level respectively, \( G_{opt} \) - the optic generation rate, \( R_{sp} \), \( R_{st} \) and \( R_{au} \) the spontaneous recombination rate, the stimulated recombination rate and the Auger recombination rate per unit volume, respectively.

APSYS software simulator includes many advanced physical models. It provides several carrier mobility options from constant values to field dependent ones.

To describe impact ionization Baraff’s model and Chynoweth’s formula have been implemented [13,14]. A generalized formula for the electron and hole impact ionization coefficients, \( \alpha \) and \( \beta \), respectively have been used:

\[
\alpha, \beta = A_c \exp \left[ - \left( \frac{F_c}{F} \right)^{\kappa_n} \right]
\]

where \( A_c \), \( F_c \) and \( \kappa_n \) are empirical parameters, which differ for electron and holes. A generation rate \( G \) for the impact ionization in the following format has been utilized:

\[
G = \left( \alpha J_n + \beta J_p \right) / q
\]

The excess noise factor \( F \) is evaluated by using following expression proposed by McIntyre [15]:

\[
F = M \left\{ 1 - \left[ 1 - \left( \frac{k_{eff}}{M - 1} \right) M \left( M - 1 \right) / M \right]^2 \right\}
\]

where \( M \)-multiplication gain, \( k_{eff} = \alpha / \beta \)
3. Simulation details
In the APD simulation procedure, the Chynoweth’s empirical model for impact ionization has been utilized. Parameters for history-dependent ionization coefficients have been applied to the ionization properties [16]. The DC device characteristics like dark current, photo-current and breakdown voltage together with a band gap diagram, electric field across the device structure have been simulated. The multiplication gain has been extracted from the photo-current I-V curve and compared with the ones at the unity gain. The excess noise factor was calculated according to McIntyre’s formula (6). In order to evaluate –3 dB bandwidth, time domain impulse response modelling has been performed. The time domain impulse response has been Fast Fourier Transformed (FFT) into the frequency response data, from which the -3 dB bandwidth has been evaluated.

4. Avalanche photodiode structure
In the design of APD the compromise between the high quantum efficiency, low dark current and the high gain-bandwidth product has to be found. Those crucial parameters for the device operation have opposite requirements. For high quantum efficiency the increase of the absorber layer thickness is desired. But this increases the travel time of the carriers thus decreases the bandwidth. In consequence, a compromise has to be settled what in certain way is arbitrary.

Here we have investigated the separate absorption, charge, grading and multiplication (SAGCM) avalanche photodiode with a relatively thick undepleted p-type InGaAs absorption region and thin InAlAs multiplication layer. The simulations were focused on the influence of the absorbing layer thickness and its doping on device performance. A number of heterostructures different in the layer thickness and doping level have been simulated. Nevertheless, SAGCM APD performance requirements strongly limit the variation of the layer parameters. The photodiode structure fulfilling the requirements for low dark current densities and low multiplication noise consisted of: a 800 nm n⁺-In0.52Al0.48As buffer layer, a 150 nm undoped In0.52Al0.48As multiplication layer, a 100 nm Be-doped (1·10¹⁷ cm⁻³) In0.52Al0.48As charge layer, a 100 nm undoped In0.52Al0.48As spacer layer, a 50 nm undoped InGaAlAs grading layer, a 1500 nm p-type In0.53Ga0.47As absorbing layer, and a 30 nm heavily Be-doped In0.5Ga0.47As p-contact layer – Table 1. The doping in the p-type absorber was changed in three 500 nm steps (5·10¹⁷ cm⁻³, 7.5·10¹⁷ cm⁻³, 1·10¹⁸ cm⁻³) to form a quasi-electric field to aid carrier transport across the absorbing layer. A 50 nm thick composition-graded InGaAlAs quaternary layer was introduced to reduce the abrupt conduction band barrier at the In0.53Ga0.47As/In0.52Al0.48As heterojunction interface. All layers forming the device structure are a lattice matched to the semi-insulating InP substrate.

Table 1. Schematic layer structure of APD with undepleted p-type absorber

| Layer     | Composition  | Type | Doping (cm⁻³) | Thickness(nm) |
|-----------|--------------|------|---------------|---------------|
| Cap       | In₀.₅₃Ga₀.₄₇As | p    | 1.0·10¹⁹      | 30            |
| Absorber  | In₀.₅₃Ga₀.₄₇As | p    | 1.0·10¹⁸      | 500           |
| Absorber  | In₀.₅₃Ga₀.₄₇As | p    | 7.5·10¹⁷      | 500           |
| Absorber  | In₀.₅₃Ga₀.₄₇As | p    | 5.0·10¹⁷      | 500           |
| Grading   | InGaAlAs     | undoped |              | 50            |
| Spacer    | In₀.₅₂Al₀.₄₈As | undoped |              | 100           |
| Charge    | In₀.₅₂Al₀.₄₈As | p    | 1.0·10¹⁷      | 100           |
| Multiplication | In₀.₅₂Al₀.₄₈As | undoped |              | 150           |
| Buffer    | In₀.₅₂Al₀.₄₈As | n    | 5.0·10¹⁸      | 800           |
| Substrate | InP          | semi-insulating |              |               |
5. Results and discussion
The very first result of the calculation is the band gap of the device at equilibrium (figure 1a). The band gap distribution across the heterostructure allows a verification of the device design. The application of the doping gradient in the absorber layer results in small tilting of the conduction band. This very small inclination is maintained at high voltage (figure 1b) for which, however, the potential drop takes place almost exclusively in the multiplication layer. Such design enhances the photo-carrier flow towards the p-n junction at the operation voltage. Otherwise, the diffusion of the carriers would be the only mechanism of the carrier transport, what for the extended thickness of the absorber layer would strongly increase the carrier transition time i.e., limits the bandwidth.

![Figure 1](image1.jpg)

Figure 1. a) The conduction and valence bands across the APD at equilibrium. In upper graph the doping levels are shown. b) The bands of biased device at the breakdown voltage.

The calculated current-voltage characteristic is shown in figure 2. In the simulation of photocurrent characteristic the value of power of the incident light equal to 1 W/cm² was assumed.

The very low dark current is below 1·10⁻¹⁰ A/cm². The breakdown voltage is 24.68 V. The small kink around 12 V is related to a conduction band barrier overflow by electrons. The height of this barrier depends on the composition of the charge layer and its doping. The composition is restricted by the lattice-matching requirement of In₀.₅₂Al₀.₄₈As to the InP substrate, but the doping level can be adjusted in certain range. The maximum limit is around 4·10¹⁷ cm⁻³. For this concentration the threshold for barrier overflow voltage corresponds to the breakdown voltage. Here slightly lower value, 1·10¹⁷ cm⁻³, has been chosen.

The current-voltage characteristics allows for the calculation of the multiplication gain (figure 3). The unity gain is at about 7 V.

For precise evaluation of the multiplication gain the electron current distribution along the heterostructure has been calculated (figure 4). The voltage dependent current increase manifests clearly. The gain is the measure of a ratio of the electron current at the absorber-grading interface and the buffer layer. In figure 4 along the currents also the electric field at breakdown voltage has been included. The maximum value in multiplication layer is equal to almost 700 kV/cm.

APD gain varies as a function of applied reverse voltage, as shown in figure 3. In addition, for many APDs, it is not possible, or practical, to make an accurate measurement of the intrinsic responsivity at a gain M=1. It is therefore inappropriate to state typical gain and diode sensitivity at M=1. In order to characterize APD responsivity, one must specify APD responsivity at a given operating voltage $V_{OP}$. Taking into account results presented in figure 2 and 3 one can estimate responsivity $R$ of simulated APD. In this case $R=0.1$ A/W at $V_{OP}=24.65$ V, $M=100$. This value of calculated responsivity is obtained for APD without any antireflection coating.
Another important issue of any APD is the bandwidth (figure 5). The gain and –3 dB bandwidth product is 165 GHz for the structure studied. The time response for 10 ps long light impulse of Gaussian shape is presented in the inset of figure 5.

**Figure 2.** The current-voltage characteristics of APD

**Figure 3.** Multiplication gain as a function of bias voltage.

**Figure 4.** The electron current and electric field along the APD heterostructure. The magnification of the current flow due to the carrier multiplication takes place in the multiplication layer where the electric field is the highest. The spike of the electric field at 0.5 µm corresponds to the InP substrate and InAlAs buffer layer interface discontinuity.

**Figure 5.** The bandwidth as a function of gain. The bandwidth-gain product is equal to 165 GHz. In an inset the time responses for the 10 ps impulse for different bias voltages are shown.
The excess noise factor $F$ has been calculated using the McIntyre’s formula. The changes of $F$ versus multiplication gain are presented in figure 6.

6. Summary
The performance of InGaAs/InAlAs/InP APD with undepleted absorber has been simulated. Very low dark current and a gain-bandwidth product of 165 GHz are the main features of this structure. Due to several characteristics this type of APD is very useful in many applications.

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