TEMPERATURE DEPENDENCE OF ELECTRON AND HOLE IONIZATION COEFFICIENTS IN InP

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Introduction

In this work we investigate the temperature dependence of the electron and hole ionization coefficients in $\langle 100 \rangle$ Indium Phosphyde, in a wide range, from 50 K to room temperature. We use InP/InGaAs $p^+n$ junctions to accurately measure the dependence of the breakdown voltage on the temperature. From the data measured during the fabrication processing, we evaluate the doping profiles and the depths of the various layers. Then we compute the electric field in the high field region. In order to take into account the dependence of the ionization coefficients on both the electric field and the temperature, we use a reported physical model. By adjusting the only fitting parameter, we obtain the complete expressions for $\alpha(E,T)$ and $\beta(E,T)$, that herewith we report, and that are in good agreement with other published data.

I. Ionization coefficients

Compound semiconductor devices are increasingly operated under high electric fields, where impact ionization plays a major role. For instance, Separate Absorption, Grading, and Multiplication (SAGM) InP/InGaAs avalanche photodiodes (APDs) are currently used in fiber-optic communication networks, working in the second and third windows where silica has the lower attenuation and dispersion, i.e. at 1.3 and 1.5 $\mu$m-wavelengths. They can be operated both in the analog multiplying regime, below but near the breakdown voltage, $V_B$, or in the so called Geiger-mode, when biased above breakdown.

The main parameters describing the ionization properties of carriers are the coefficients $\alpha$ for electron and $\beta$ for hole defined as the reciprocal of the carrier average mean free path between subsequent ionizing collisions. These parameters are highly dependent on physical, technological and geometrical properties of the semiconductor. In order to squeeze out the best performance from devices like APDs, a fine tailoring of the electric field and the doping profiles at the junction must be pursued.

In device modelling and design it is very important to know the dependence of both electron and hole ionization coefficients on the electric field, $E$. So far, despite various experiments were performed at 300 K in InP/InGaAs devices, only few works dealt with the dependence of $\alpha$ and $\beta$ on the temperature, $T$, and their results are incomplete and usually in disagreement.

Purpose of this work was to proceed in a quantitative verification of some of the most common reported physical models. We sorted out the physical model and we adapted the temperature dependence. By adjusting the only fitting parameter and comparing our reproducible experimental data with the computed ones, we obtained a best fitting. In this paper we report the two detailed expressions for $\alpha(E,T)$ and $\beta(E,T)$ in $\langle 100 \rangle$ InP, verified from room temperature down to 50 K, for maximum electric fields of $5.5 \times 10^5$ $V/cm$.

II. The samples

Figure 1 shows the cross section of the sample, an InP/InGaAs APD, grown by Vapour Phase Epitaxy. The $n^+$ InP $\langle 100 \rangle$ substrate is covered by a 3 $\mu$m-thick $n$ InP buffer layer. The photon absorbing region is a 4 $\mu$m-thick $n$ InGaAs layer with a doping level of $1.5 \times 10^{15}$ $cm^{-3}$. A 50 nm-thick InGaAsP layer is grown before the intermediate $n$ InP 2 $\mu$m-layer ($1.5 \times 10^{15}$ $cm^{-3}$ doping). A controlled silicon ($\delta$-type) ion implantation of $2.5 \times 10^{15}$ $cm^{-2}$ defines the high field region in InP, and provides a uniform field distribution over the whole sample active area. The final top 3.4 $\mu$m-thick $n$ InP layer is then regrown. The junction is eventually fabricated by a zinc $p$ diffusion in the InP.

At room temperature, the breakdown voltage of these samples is about 100 $V$. The silicon ion implantation mask, having a diameter smaller than the zinc diffusion mask, provides a virtual guard ring around the high-field region, thus preventing edge effects and anomalous avalanche triggering.
The InP-InGaAs heterointerface causes a potential step of about 0.62 eV in the valence band, shown in Fig. 2. Therefore, when the APD is reverse biased, holes photogenerated in the InGaAs layer suffer from pile-up before jumping across the step, by thermoionic emission. For this reason, in order to improve the performance of such detectors, the quaternary InGaAsP layer was adopted, with an intermediate gap of 1.05 eV, which smoothes the valence band discontinuity.

III. Experimental data

We put the samples inside a variable cryostat and we cooled them from room temperature down to 50 K. The samples were connected to a precision electrometer (Keithley 617), controlled by a computer for the acquisition of the measurements and the computing operations. We measured the complete current-voltage, I/V, curves at various temperatures, by reverse biasing the junction. Figure 3 reports the I/V curves measured at five temperatures. As can be seen, the lower the temperature, the sharper the avalanche multiplication rise and the lower the breakdown voltage.

In order to gain more insight from the InP/InGaAs structure, we decided to shine the samples with a 1.3 µm-wavelength laser: at this wavelength, photons are absorbed only in the inner InGaAs layer and the photocurrent is mainly due to photogenerated holes that must jump the heterojunction in order to reach the junction high field region and contribute to the reverse current, otherwise they pile-up and then recombine. The presence of an electric field at the heterointerface can efficiently reduce this step, thus improving the hole crossing probability. For temperatures higher than 100K, we see in Fig. 3 that a minimum reverse bias of

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**Fig. 1** Cross section of the InP/InGaAs samples.

**Fig. 2** Energy band diagram of the InP/InGaAs samples, when reverse biased.

**Fig. 3** Photocurrents vs. applied reverse voltage at different temperatures, when a 1.3µm-wavelength laser is shining on the samples.

**Fig. 4** Measured breakdown voltage of the InP samples (dots) and computed values (solid line) obtained by using the expressions for α(E,T) and β(E,T) reported in the paper.
about 10 V is needed to have a non-negligible current. At this bias, the junction depleted region at the edge of the silicon implantation reaches the heterointerface and photogenerated holes begin to be collected at the junction edge. At temperatures lower than 100 K, the freezing out of the zinc dopant and the reduction of holes thermoionic energy increase the electric field required to enhance the crossing, as shown in Fig. 3 (about 20 V at 77 K and 25 V at 50 K).

At about 14 V, the lowering of the heterobarrier step at the edge of the silicon implant is sufficient to collect all the photogenerated holes that diffuse to that region, and the photocurrent remains constant even if the bias is raised further. Only at 32 V the junction depleted region can reach the heterointerface underneath the silicon implanted area. Here again it corresponds to another knee in the $I/V$ characteristics (not clearly visible in Fig. 3), since only now photogenerated holes can cross the heterobarrier under the high field region thus triggering the avalanche multiplication process. The difference between this latter voltage and the previous 10 V, together with the implanted silicon dose accurately measured during the fabrication, let us estimate in 0.4 $\mu$m the distance of the silicon implant from the junction.

After the characterization of all these parameters, we measured the breakdown voltage of the InP APDs by cooling the samples in the range 50-300 K. The experimental data are reported in Fig. 4 with dots. We verified that there were no microplasmas over the active area that could lead to erroneous interpretation of the ignition of the avalanche process.

### IV. Device Modelling

In order to compute the electric field distribution in the junction, the doping profiles of the zinc diffusion must be known. We used the expression of the anomalous distribution of zinc in InP reported in Ref. 9, with an exponential decay, $C(x)=C^0 \exp(-6.3 x/\lambda)$, from a peak concentration of $C^0$ down to a diffusion depth $\lambda$, beyond which the zinc concentration quickly drops to negligible values. From the temperature and time duration used in the fabrication of our samples, we estimated $C^0=1.7 \times 10^{19}$ cm$^{-3}$ and $\lambda=3.2$ $\mu$m.

By using all the doping profiles, the silicon implant dose and the widths of the various InP and InGaAs layers measured during the fabrication processes, we simulated the local electric field $E$ in the samples, by means of an iterative solution of the Poisson equation. Figure 5 shows the computed electric field and potential distributions in the sample active area at 77 K and 300 K, corresponding to the measured breakdown voltages of 51 V and 102 V respectively.

We tested the empirical expressions for $\alpha(E)$ and $\beta(E)$ reported in literature for room temperature, by computing the ionization integral, $I$, in the high field region, as proposed in Ref. 10, and by recursively iterating the reverse voltage until the breakdown

\[
\alpha(E, T) = \frac{qE}{E_{th}^\alpha} \exp \left\{ 0.217 \left( \frac{E_{th}^\alpha}{E_{th}^\alpha} \right)^{1.14} - \left[ 0.217 \left( \frac{E_{th}^\alpha}{E_{th}^\alpha} \right)^{1.14} \right]^2 + \left( \frac{E_{th}^\alpha}{qEX^\alpha} \right)^2 \right\}^{0.5}
\]

\[
\alpha^\alpha = 1.9 \text{eV}
\]

\[
\lambda^\alpha = 41.7 \AA \cdot \tanh \left( \frac{46 \text{meV}}{2kT} \right)
\]

\[
E_R^\alpha = 46 \text{meV} \cdot \tanh \left( \frac{46 \text{meV}}{2kT} \right)
\]

\[
\beta(E, T) = \frac{qE}{E_{th}^\beta} \exp \left\{ 0.217 \left( \frac{E_{th}^\beta}{E_{th}^\beta} \right)^{1.14} - \left[ 0.217 \left( \frac{E_{th}^\beta}{E_{th}^\beta} \right)^{1.14} \right]^2 + \left( \frac{E_{th}^\beta}{qEX^\beta} \right)^2 \right\}^{0.5}
\]

\[
\beta^\beta = 1.4 \text{eV}
\]

\[
\lambda^\beta = 41.3 \AA \cdot \tanh \left( \frac{36 \text{meV}}{2kT} \right)
\]

\[
E_R^\beta = 36 \text{meV} \cdot \tanh \left( \frac{36 \text{meV}}{2kT} \right)
\]
condition $l=1$ was met. The corresponding voltage is the breakdown voltage compatible with the chosen parameters $\alpha(E)$ and $\beta(E)$.

Since all the simulations gave different values, we decided to use a more physical model, based on the Baraff theory, by means of the Okuto-Crowell's expressions for $\alpha(E)$ and $\beta(E)$. We introduced the temperature dependence by scaling the physical parameters with the Crowell-Sze relations and we used the parameters already assessed in literature, apart from the threshold ionization energies, $E_{th}^\alpha$ and $E_{th}^\beta$, for electron and hole respectively. These were the only fitting parameters in the simulation, and we scaled them with the same temperature shift coefficient of the InP energy gap, namely $-2.9 \times 10^{-4}$ eV/K, due to the extended temperature range of our investigation. The final expressions $\alpha(E,T)$ and $\beta(E,T)$ are shown in the previous page.

From the comparison of the $V_G(T)$ obtained by the simulation and the experimental data, we adjusted the only fitting parameters, to reach the best fitting, shown in Fig.4 in solid line. The obtained values are $E_{th}^\alpha=1.9$ eV and $E_{th}^\beta=1.4$ eV. The expressions we report, when evaluated at 300K, are in good agreement with the data obtained in a full-band Monte Carlo simulation by Chandramouli et al. and with the expressions of $\alpha(E)$ and $\beta(E)$ obtained by Armiento, but valid only at room temperature.

Figures 6 and 7 show the complete temperature and electric field dependence of $\alpha$ and $\beta$ respectively. It is worth to note that the maximum electric field experienced within our samples is about 530 kV/cm at room temperature, and decreases to 450 kV/cm at 77K, as shown in Fig.5. Work is in progress in order to validate these expressions even at different electric field profiles and doping levels.

References