Monte Carlo model for the analysis and development of III-V Tunnel-FETs and Impact Ionization-MOSFETs

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Abstract. Impact-ionization metal-oxide-semiconductor FETs (I-MOSFETs) are in competition with tunnel FETs (TFETs) in order to achieve the best behaviour for low power logic circuits. Concretely, III-V I-MOSFETs are being explored as promising devices due to the proper reliability, since the impact ionization events happen away from the gate oxide, and the high cutoff frequency, due to high electron mobility. To facilitate the design process from the physical point of view, a Monte Carlo (MC) model which includes both impact ionization and band-to-band tunnel is presented. Two ungated InGaAs and InAlAs/InGaAs 100 nm PIN diodes have been simulated. In both devices, the tunnel processes are more frequent than impact ionizations, so that they are found to be appropriate for TFET structures and not for I-MOSFETs. According to our simulations, other narrow bandgap candidates for the III-V heterostructure, such as InAs or GaSb, and/or PININ structures must be considered for a correct I-MOSFET design.

1. Introduction

Impact-ionization metal-oxide-semiconductor FETs (I-MOSFETs) have demonstrated to provide a subthreshold slope (SS) as low as ~4 mV/dec, one order of magnitude lower than those obtained with classical MOSFETs with a similar I_{on} [1]; however, the necessary source-to-drain voltage V_{DS} is still too large to be competitive with mainstream MOSFET technology. On the other side, III-V MOSFETs can work at V_{DS} lower than 0.5 V and deliver I_{on} currents near 1 A/mm [2], but with a large value of SS. Reliability is also an issue due to the degradation of the gate oxide. In order to overcome these weaknesses, III-V I-MOSFETs are being explored as promising devices for ultra-low power logical circuits. By means of an adequate heterostructure bandgap engineering, these devices should be able to improve both the reliability (by moving the impact ionization events away from the gate oxide) and the cutoff frequency (due to the higher mobility of III-V materials). The first option under study is InGaAs heterostructures because of the mature technology, but, as shown later, the tunnel effect appears for lower applied V_{DS} than impact ionization processes, thus making this behavior impossible as an I-MOSFET. In fact, tunnel-FETs (TFETs) [3] are direct opponents of I-MOSFETs for ultra-low SS digital applications. As an alternative, InAs-based heterostructures will have to be used for the fabrication of I-MOSFETs.

In order to support the development of III-V I-MOS transistors, and as an alternative to the test-and-error experimental procedure, this work reports the development of a Monte Carlo (MC) model, which incorporates impact ionization processes by means of the Keldysh approach [4,5] as well as band-to-band tunnel by means of the Wentzel-Kramers-Brillouin (WKB) method [6]. MC simulations are useful for the study of narrow bandgap III-V heterostructures from the physical point of view as well as ungated and gated PIN topologies. This model allows identifying the competition between the impact ionization and band-to-band tunneling at the onset of the conduction in InGaAs-based PIN diodes. As well, it can assist the design and optimization of I-MOSFET topologies in terms of I_{off} and I_{on} currents, V_{DS} and SS.

2. Physical Model

For the calculations we make use of an ensemble MC simulator self-consistently coupled with a 2D Poisson solver, which includes a detailed model for the hole transport, impact ionization processes and band-to-band tunnel, valid for the simulation of ungated $In_{0.53}Ga_{0.47}As$ and lattice matched InAlAs/InGaAs-based PIN diodes. The parameters for electrons in the involved materials can be found in Ref. [7]. The model used for hole dynamics is essential due to the P-region. A typical spherical and nonparabolic valence band structure is considered, including three sub-bands: heavy- and light-hole bands (HH and LH), degenerated at k=0 and characterized by a different curvature in k-space, and a third split-off band (SOH), in which the band warping is accounted for by the use of approximated overlap functions [9]. Ionized impurity, acoustic, polar and non-polar optical phonon scattering mechanisms are considered for holes [8,9]. The hole physical parameters used in the simulations are reported in [4,5]. To illustrate the hole transport in bulk InGaAs, Figure 1 presents (a) the mean velocity in the electric field direction and (b) the mean energy as a function of the electric field for different dopings.

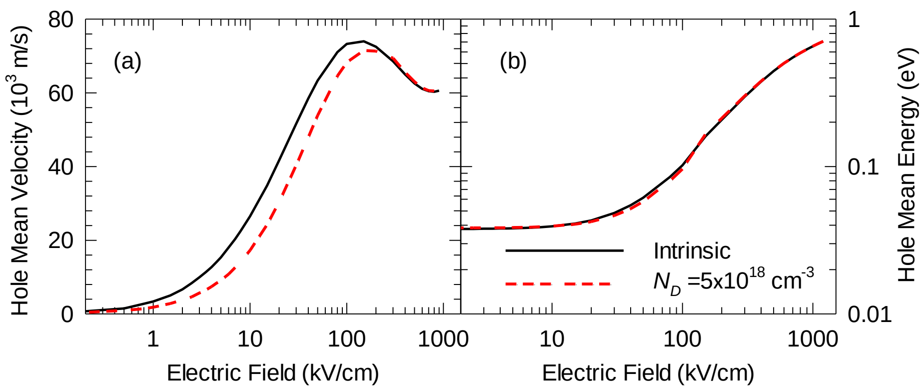

Figure 1. (a) Mean velocity in the electric field direction and (b) mean energy for holes in bulk InGaAs as a function of electric field for different P-type ionized impurity densities.

Impact ionization of electrons, which occurs in the Γ valley and leads to the generation of electron-hole pairs, is included in the MC simulator by using the Keldysh approach [10], where the probability per unit time of having an impact ionization event is given by $P(E)=S[(E- E_{th})/ E_{th}]^2$ if $E > E_{th}$, and $P(E)=0$ otherwise, E being the electron kinetic energy in the Γ valley, E_{th} the ionization threshold energy and S a measure of the softness or hardness of the threshold. E_{th} and S are considered as adjustable parameters to reproduce the ionization coefficients measured in bulk materials but they can be considered as adjustable parameters due to the large dispersion in the experimental measurements [11-14]. From each impact ionization occurrence, an electron in the Γ valley and a hole in the heavyhole band emerge, while the electron originating the ionization process remains in the Γ valley. We have verified that hole impact ionization is negligible for the considered applied voltages [4].

Our MC simulator includes also band-to-band tunneling based on the WKB method [6], essential to reproduce the physical behavior of III-V PIN diodes in reverse bias conditions. In order to consider the injection from the P-region into the intrinsic layer of the PIN diode, we perform a discretization of the incident electrons energy and calculate the number of injected particles by tunnel effect at each time step (Δt=1 fs) in the whole energy range, as in Refs. [15-17]. The transmission coefficient through the energy barrier $qV(x)$ is calculated following the WKB model [6, 17], while the potential profile $V(x)$ is updated at each time step from the solution of the Poisson equation in the MC simulation. The Richardson constant A^* [15] can be considered as an adjustable parameter in the simulations in order to perform future experimental adjustments.

3. Results

Figure 2 shows (a) the I-V characteristics for reverse bias and (b) the position of tunnel events and impact ionization processes results provided by the MC model for a 100 nm PIN diode based on $In_{0.53}Ga_{0.47}As$, being the intrinsic reverse bias V=-3.0 V. In Figure 2(b) the energy bands have been included for clarity. The parameters considered for tunneling are of the order of those found for bulk [17] while the impact ionization probability has been exaggerated to check the possibility of being the dominant effect. Tunnel events take place along the intrinsic region, constrained by the shape of the energy bands. As well, impact ionization appears mainly at the N-side of the intrinsic region of the structure, where the electric field and then the electron energy reach the higher values. Tunnel effect is always the most significant mechanism, in fact, the impact ionization takes place just when there are enough electrons generated by tunnel effect in the P-side of the intrinsic region. Then, in the absence of tunneling, there is not any impact ionization event recorded in our simulations. Nevertheless, as can be seen in Figure 2(a), the value of I_{on} is enhanced by the presence of impact ionization mechanisms.

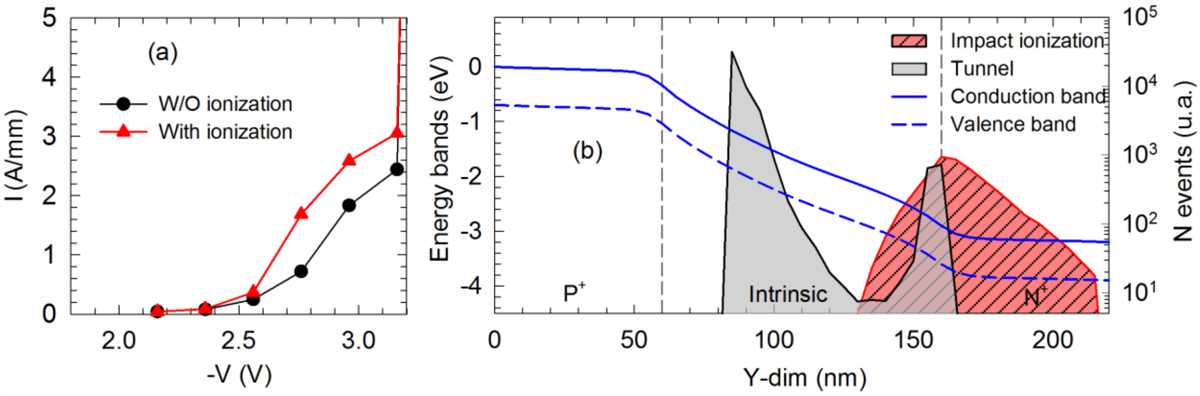

Figure 2. (a) I-V curves and (b) conduction and valence band energy bands, impact ionization and tunnel events for a InGaAs 100 nm PIN diode, being the reverse bias V=-3.0 V.

A 100 nm PIN diode based on the lattice-matched InAlAs/InGaAs heterostructure has been also qualitatively studied and simulation results have been obtained. The existence of impact ionization events, even if it is overestimated, does not lead to a significant enhancement in the I-V curves. For simplicity, Figure 3 presents (a) the I-V characteristics and (b) the position of just tunnel events in the absence of impact ionization. The reverse bias necessary for the achievement of I_{on} is of the order of that found for the InGaAs structure.

4. Conclusions

A MC model which incorporates impact ionization processes by means of the Keldysh approach and band-to-band tunnel by means of the WKB method has been developed for the study of narrow

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bandgap III-V heterostructures in order to support the development of III-V I-MOS transistors. The physical behavior of 100 nm PIN diodes based in InGaAs and InAlAs/InGaAs have been qualitatively analyzed to evaluate the competition between tunnel and impact ionization events. Even when the impact ionization is overestimated, the stronger physical process is the tunnel injection. Other narrow bandgap candidates for the III-V heterostructure, as InAs or GaSb, must be considered. As well, since the tunnel I_{on} of InGaAs homostructures can be improved when impact ionization takes place, designing PININ structures can also been considered for the development of III-V I-MOSFETs.

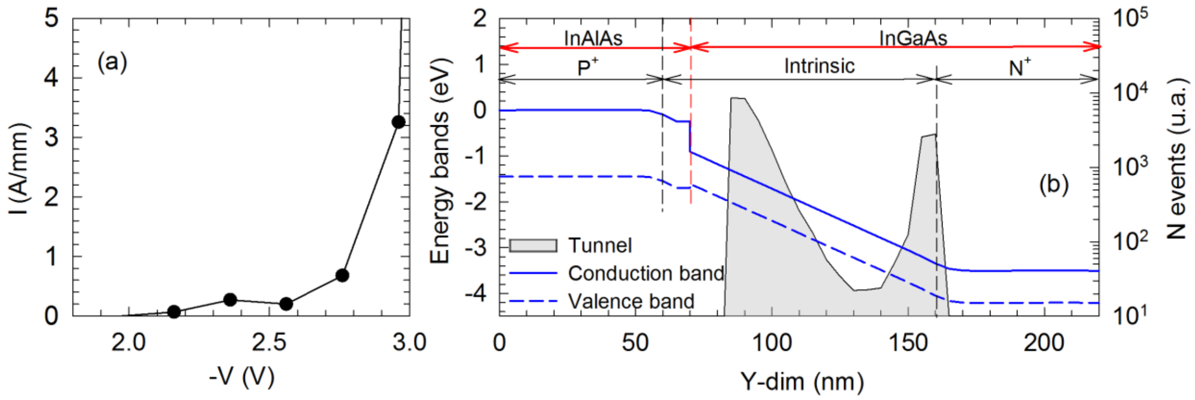

Figure 3. (a) I-V curves and (b) conduction and valence band energy bands, and tunnel events for a PIN diode based in the heterostructure InAlAs/InGaAs, being the reverse bias V=-3.0 V.

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References

[1] Q. Huang, R. Huang, Z. Wang, Z. Zhan and Y. Wang 2011 *Appl. Phys. Lett.* **99** 083507
[2] J. J. Gu, Y. Q. Wu and P. D. Ye 2011 *J. Appl. Phys.* **109** 053709
[3] W. Y. Choi, J. Y. Song, J. D. Lee, Y. J. Park and B.-G. Park 2005 *IEEE Inter. Electron devices Meeting (IEDM)* 955
[4] B. G. Vasallo, J. Mateos, D. Pardo and T. González 2003 *J. Appl. Phys.* **94** 4096
[5] B. G. Vasallo, J. Mateos, D. Pardo and T. González 2004 *J. Appl. Phys.* **95** 8271
[6] B. H. Bransden and C. J. Joachain 1987 *Introduction to Quantum Mechanics* New York: Longman Scientific & Technical
[7] J. Mateos, T. González, D. Pardo, V. Hoël and A. Cappy 1999 *Semicond. Sci. Technol.* **14** 864
[8] T. Brudevoll, T. A. Fjeldly, J. Baek and M. S. Shur 1990 *J. Appl. Phys.* **67** 7373
[9] M. Costato and L. Reggiani 1973 *Phys. Stat. Sol. (b)* **58** 471
[10] M. V. Fischetti 1991 *IEEE Trans. Electron Devices* **38** 634
[11] T. P. Pearsal 1980 *Appl. Phys. Lett.* **36** 218
[12] F. Osaka, T. Mikawa and T. Kaneda 1985 *IEEE J. Quantum Electron.* **21** 1326
[13] T. Kagawa, Y. Kawamura, H. Asai, M. Naganuma and O. Mikami 1989 *Appl. Phys. Lett.* **55** 993
[14] I. Watanable, T. Torikai, K. Matika, K. Fukushima and T. Uji 1990 *IEEE Electron Device Lett.* **11** 437
[15] D. Moro-Melgar, J. Mateos, T. González and B. G. Vasallo 2014 *J. Appl. Phys.* **116** 234502
[16] Sun L., Liu X. Y., Liu M., Du G. and Han R. 2003 *Semicond. Sci. Technol.* **18** 576
[17] Huang C.K., Zhang W. E. And Yang C. H. 1998 *IEEE Trans. on Electron Devices* **45** 4