Modelling of Schottky-Barrier Diodes Operating under Strong Reverse-Bias Conditions

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ABSTRACT

We report on a Monte Carlo (MC) model which includes the physical phenomena necessary to correctly simulate Schottky-barrier diodes (SBDs) operating under strong reverse-bias conditions, particularly relevant to regions of the diodes where a very high electron tunnel injection takes place, like the contact edge or surface inhomogeneities. The model is applied to the analysis of GaN diodes with 1D and (more realistic) 2D topologies.

INTRODUCTION

The correct modelling of reverse current in SBDs is essential to predict their breakdown. Ideal thermionic-emission and tunneling currents are typically estimated assuming full depletion (FD) in the semiconductor adjacent to the metal [1]. However, in regions of the diode surface where the number of injected electrons is very high, the FD assumption does not hold anymore. In such a case, the barrier profile determining electron tunnel injection must be self-consistently calculated with carrier concentration in the partially depleted region, being necessary the simulation of carrier transport. Impact ionization (II) initiated by the injected electrons, and also by the generated holes, is especially critical, since very high electric fields are reached, particularly in some regions like the contact edges [2]. In this work we address this issue for the case of GaN SBDs by means of MC simulations where all the involved physical effects are carefully modeled.

MODEL

The model includes tunnel injection with barrier lowering [3], electron and hole transport [4,5], with II implemented by means of the Keldysh approach [5], and self-consistency between the shape of the energy barrier and carrier concentration in the adjacent semiconductor [6].

RESULTS

Fig. 1 shows the I-V curves calculated at 300 K for a large-area GaN SBD (1D geometry, uniform in transversal direction) with active region length 1.0 μm, doping 4×10^{17} cm^{-3} and barrier height 0.6 eV. As observed, the FD assumption overestimates the current, and the contribution of the carriers generated by II events (triangles), calculated as the hole current at the Schottky contact (SC), becomes relevant for voltages beyond -40 V. As shown by Fig. 2, electrons injected by tunneling at the SC gain energy from the very high field inside the device [see Fig. 3(b)] and originate II events as they drift left. Generated holes, in turn, also originate II processes while moving right towards the SC. As a result, carrier concentrations exhibit the profiles shown in Fig. 3(a). Note the relevant differences existing between the results (current level, carrier concentration, electric field profile) obtained with and without considering II [6].

In more realistic diodes with 2D geometries, very high values of the electric field as those reached in the previous 1D structure are found near the contact edge, region at which avalanche breakdown may be initiated [2]. Such effects can be mitigated by the selection of an appropriate passivation dielectric [7]. Fig. 4 reports results corresponding to the small-area 2D GaN diode sketched in Fig. 4(a) [barrier height 0.5 eV, I-V curve in Fig. 4(b)]. Figs. 4(c) and (d) show the electron concentration for an applied voltage of -30 V considering air and Si_3N_4 as passivation dielectric. As observed, tunnel injection is much more pronounced at the contact edge, where the vertical electric field is stronger, this effect being reduced using a higher κ dielectric, like Si_3N_4. Figs. 4(e) and (f), corresponding to -40 V and air as dielectric, show electron and hole concentration. For this bias the epilayer is totally depleted. The high hole density near the contact edge evidences that significant II is taking place, ultimately leading to the avalanche breakdown of the device when the bias is further increased ($V_{break} \approx -68$ V).

ACKNOWLEDGMENTS

This work has been partially supported through Grant PID2020-115842RB-I00 funded by MCIN/ AEI/10.13039/501100011033. B. Orfao thanks the PhD contract from the Junta de Castilla y León.

REFERENCES

[1] W. Li, D. Saraswat, Y. Long, K. Nomoto, D. Jena, and H. G. Xing, Appl. Phys. Lett. **116**, 192101 (2020).

[2] X. Liu, F. Lin, J. Li , Y. Lin, J. Wu, H. Wang, X. Li, S. Huang, Q. Wang, H.-C. Chiu, and H. C. Kuo, IEEE Trans. Electron. Dev. **69**, 1938 (2022).

[3] B. Orfao, G. Di Gioia, B. G. Vasallo, S. Pérez, J. Mateos, Y. Roelens, E. Frayssinet, Y. Cordier, M. Zaknoune, and T. González, J. Appl. Phys. **132**, 044502 (2022).

[4] S. García, S. Pérez, I. Íñiguez-de-la-Torre, J. Mateos, and T. González, J. Appl. Phys. **115**, 044510 (2014).

[5] S. Chen and G. Wang, J. Appl. Phys. **103**, 023703 (2008).

[6] T. González, B. Orfao, S. Pérez, J. Mateos, and B. G. Vasallo, Appl. Phys. Express (2023). DOI :10.35848/ 1882-0786/acb9d4

[7] B. Orfao , B. G. Vasallo, S. Pérez, J. Mateos, D. Moro-Melgar, M. Zaknoune, and T. González, IEEE Trans Electron Dev. **68**, 4296 (2021).

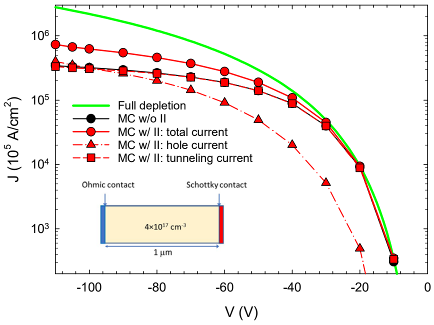

Fig. **1**. I-V curve under reverse bias conditions calculated at 300 K for the diode in the inset using different models (FD assumption, MC without and with II) jointly with hole and tunneling contributions at the SC in the case of MC with II.

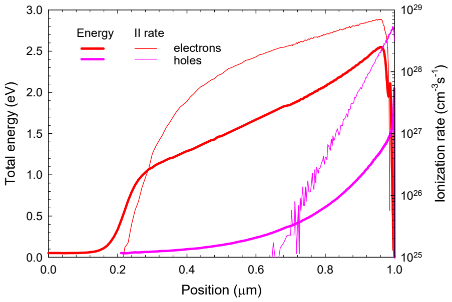

Fig. 2. Profiles of total average energy and II rate of electrons and holes for a bias voltage of -100 V.

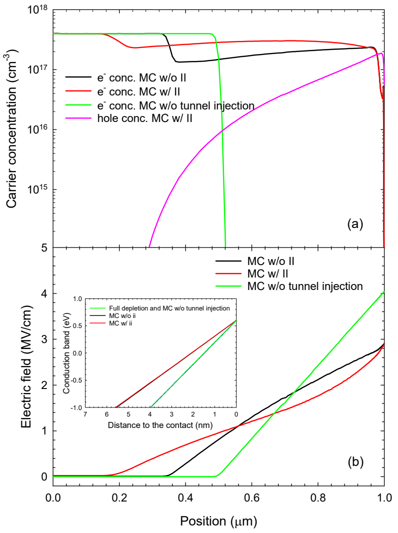

Fig. 3. (a) Profiles of carrier concentration for V= -100 V calculated with and without considering II in MC simulations, as well as without tunnel injection. (b) Corresponding electric field profiles. The inset shows the conduction band at the SC for the same cases (with the metal Fermi level as zero-energy reference) compared with the FD approximation.

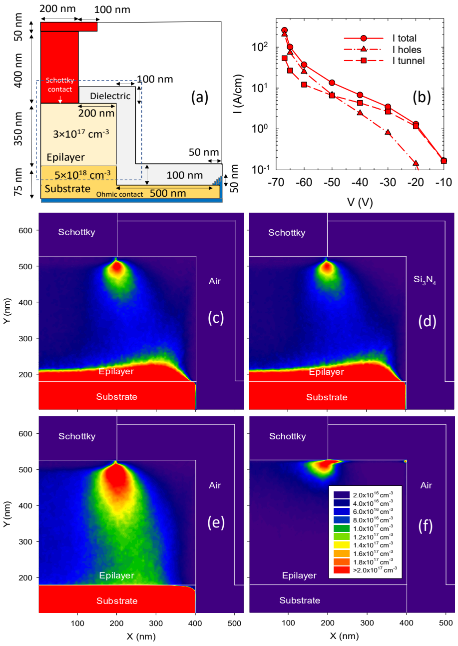

Fig. 4. (a) Sketch of the 2D diode. (b) I-V curve. Color maps of electron concentration for an applied voltage of -30 V in the area delimited in (a) by the dashed rectangle using: (c) air and (d) Si_3N_4 as passivation dielectrics. (e) Electron and (f) hole concentration for V= -40 V and air as dielectric.