A Full-Band Monte Carlo Study of Gain, Bandwidth and Noise of GaN Avalanche Photodiodes

Michele Moresco*, Francesco Bertazzi*†, Enrico Bellotti*
* ECE Department, Boston University, 8 Saint Mary's Street, 02215 Boston, MA, USA
† Dipartimento di Elettronica, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

Abstract—A growing number of system applications are increasingly demanding high speed, low noise, and high sensitivity UV detectors. GaN avalanche photodiodes (APDs) are prime candidates to become the device of choice in this area. This work presents a theoretical analysis of the performance of GaN APDs using Full Band Monte Carlo simulation. A study of the multiplication gain, noise and bandwidth is presented in this paper. The numerical results are in good agreement with experimental data available in literature.

I. INTRODUCTION

GaN-based APDs are particularly important for applications where solar blind detection is necessary. The recent APD design trend, both for conventional III-V and III-Nitride semiconductors, feature very thin multiplication regions, which lead to a significant improvement in noise characteristics. The conventional gain and noise model developed by McIntyre [1], which assumes that impact ionization is a continuous and local process, is not applicable in thin structures [2]. This is because nonlocal effects, such as dead space and drift velocity overshoot, become significant in these devices. Among suitable numerical techniques, the Monte Carlo method is the most appropriate tool to study the avalanche multiplication process in APDs. In the present work we use a Full Band Monte Carlo (FBMC) model that makes use of the full electronic structure computed from the nonlocal empirical pseudopotential method (NL-EPM). Screened atomic potentials are selected to accurately reproduce the main energy gaps, effective masses, charge density and dielectric function as obtained from experiments and from $ab - initio$ calculations. Band-to-band tunneling is treated by employing the Krieger-Iafrate model [3] following the approach described in [4]. The lattice dynamics is determined using the linear-response method within density-functional perturbation theory [5]. Phonon-carrier scattering rates are determined from the Fermi's golden rule accounting for the band structure and the lattice dynamics within the rigid pseudoion (RPI) formalism [6]. The calculation of the electron- and hole-initiated impact ionization rates is performed to first order by using the Fermi golden rule [7] within the EPM full band structure context. The model is described in detail in [8].

II. RESULTS

A detalied analysis of the multiplication gain for a number of APDs fabricated and characterized by several research groups [9]–[13] was presented in [14]. For electron (hole) initiated multiplication, an electron (hole) is injected from one edge of the multiplication region and the motion of the primary carrier and of the carriers generated subsequently are considered simultaneously within the MC framework. The electron (hole) multiplication, G_e (G_h), for such a trial is given by the total number of carriers, of the type injected, which exit on the far side. A comparison between calculated multiplication gains and experimental data is shown in Fig. 1 [14]. Despite the unavoidable uncertainties in the details of the device structure, a very good agreement with experimental data was obtained.

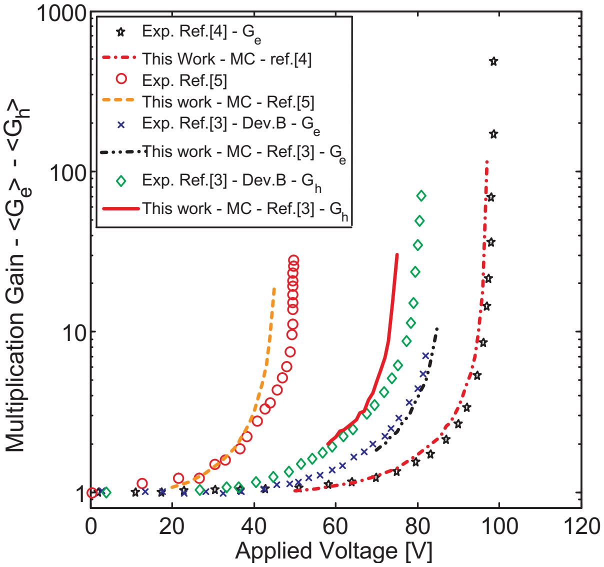

Fig. 1. Comparison between the measured electron and hole multiplication gain data available in the literature and the calculated values obtained using the proposed Monte Carlo model: [a] measured (black pentagons) and calculated (red dash-dot line) electron multiplication gain for the device of Dupuis and coworkers [12], [b] measured (red circles) and calculated (dashed orange line) electron multiplication gain for the device reported by Carrano and coworkers [13], [c] measured (green diamond) and calculated (red solid line) hole multiplication gain, measured (blue x symbols) and calculated (black dash-two-dot line) electron multiplication gain for the device reported by McClintock and coworkers [11].

In the present work we compute the noise properties of GaN-APDs. The electrom (hole) excess noise factor F_e (F_h) are defined as the normalized second moments of the mul-

978-1-4244-7017-4/10/$26.00 ©2010 IEEE

tiplication random variables G_e (G_h) and can be directly extracted from the Monte Carlo simulations. The elecron excess noise computed as a function of gain for different widths of the multiplication region is presented in Fig. 2. As the multiplication region is reduced, the excess noise decreases as multiplication becomes a more confined process and therefore more deterministic [15].

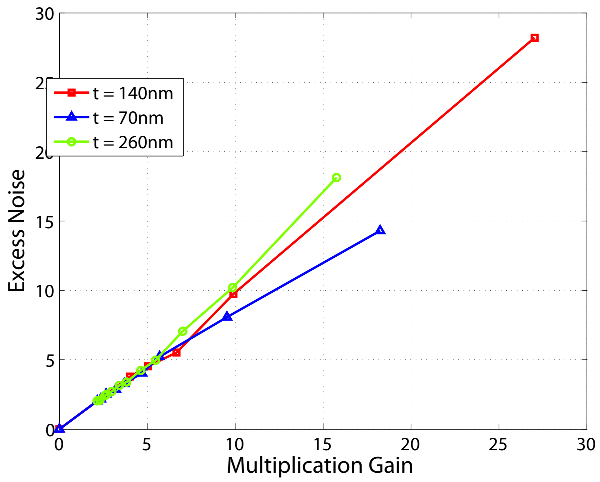

Fig. 2. Excess noise computed as a function of multiplication gain. The thickness of the multiplication region is varied from 70 nm to 260 nm.

The APD bandwidth is obtained by Fourier transforming the time response. Fig. 3 shows the bandwidth as a function of the gain, for a multiplication region thickness $t = 70$ nm and $t = 140$ nm. Both curves present two different regions. On the left, the bandwidth is approximately constant and the limiting mechanism is given by the hole transit time across the quasi-neutral region [16]. In fact as holes exit the multiplication region their velocity drops significantly more than that of electrons. This is due to the fact that electrons undergo velocity overshoot while holes do not. However, as gain increases impact ionization becomes the main mechanism that limits the bandwidth. Consequently the gain-bandwidth product is constant, and equal to 216 GHz and 600 GHz for $T = 140$ nm and $T = 70$ nm, respectively.

ACKNOWLEDGMENTS

E. Bellotti and M. Moresco were supported by the 2005 NSF CAREER Award ECS-0449232. F. Bertazzi was supported by the Boston University Photonics Center and ARL.

REFERENCES

[1] R. J. McIntyre, “Multiplication noise in uniform avalanche diodes,” *IEEE Trans. Electron Devices*, vol. 13, no. 1, pp. 164–168, Jan. 1966.

[2] M. M. Hayat, W. L. Sargent, and B. E. A. Saleh, “Effect of dead space on gain and noise in Si and GaAs avalanche photodiode,” *IEEE J. Quantum Electron.*, vol. 28, no. 5, pp. 1360–1365, May 1992.

[3] J. B. Krieger and G. J. Iafrate, “Time evolution of Bloch electrons in a homogeneous electric field,” *Phys. Rev. B*, vol. 33, no. 8, pp. 5494–5500, Apr. 1986.

[4] U. Lindefelt, H.-E. Nilsson, and M. Hjelm, “Choice of the wavefunction phases in the equations for electric-field-induced interband transitions,” *Semiconductor Sci. Tech.*, vol. 19, pp. 1061–1066, 2004.

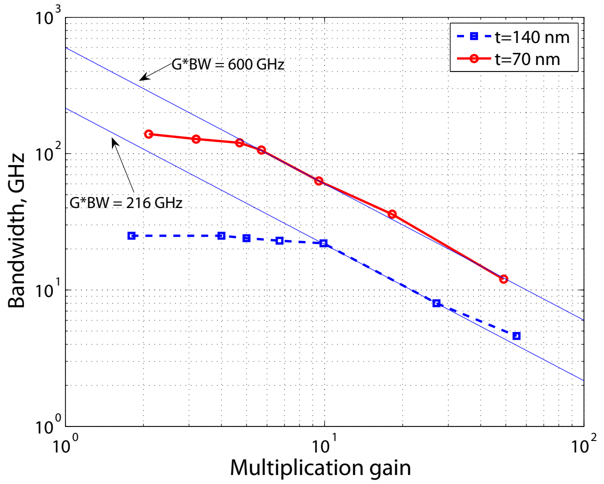

Fig. 3. Bandwidth computed as a function of gain for $t = 70$ nm and $t = 140$ nm, respectively. Also shown are the constant gain-bandwidth product functions.

[5] X. Gonze and C. Lee, “Dynamical matrices, Born effective charges, dielectric permittivity tensors, and interatomic force constants from density-functional perturbation theory,” *Phys. Rev. B*, vol. 55, no. 16, pp. 10 355–10 368, Apr. 1997.

[6] M. V. Fischetti and J. M. Higman, “Theory and calculation of the deformation potential electron-phonon scattering rates in semiconductors,” in *Monte Carlo Device Simulation: Full Band and Beyond*, K. Hess, Ed. Boston: Kluwer Academic Publishers, 1991, ch. 5, pp. 123–160.

[7] E. O. Kane, “Electron scattering by pair production in silicon,” *Phys. Rev.*, vol. 159, no. 3, pp. 624–631, July 1967.

[8] F. Bertazzi, M. Moresco, and E. Bellotti, “Theory of high field carrier transport and impact ionization in wurtzite GaN. Part I: A full band Monte Carlo model,” *J. Appl. Phys.*, vol. 106, no. 6, p. 063718, Sept. 2009.

[9] J. B. Limb, D. Yoo, J. H. Ryou, W. Lee, S. C. Shen, R. D. Dupuis, M. L. Reed, C. J. Collins, M. Wraback, D. Hanser, E. Preble, N. M. Williams, and K. Evans, “GaN ultraviolet avalanche photodiodes with optical gain greater than 1000 grown on GaN substrates by metal-organic chemical vapor deposition,” *Appl. Phys. Lett.*, vol. 89, no. 1, p. 011112, 2006.

[10] S. Verghese, K. A. McIntosh, R. J. Molnar, L. J. Mahoney, R. L. Aggarwal, M. W. Geis, K. M. Molvar, E. K. Duerr, and I. Melngailis, “GaN avalanche photodiodes operating in linear-gain mode and geiger mode,” *IEEE Trans. Electron Devices*, vol. ED-48, no. 3, pp. 502–511, Mar. 2001.

[11] R. McClintock, J. L. Pau, K. Minder, C. Bayram, P. Kung, and M. Razeghi, “Hole-initiated multiplication in back-illuminated GaN avalanche photodiodes,” *Appl. Phys. Lett.*, vol. 90, p. 141112, Apr. 2007.

[12] R. D. Dupuis, J.-H. Ryou, S.-C. Shen, P. D. Yoder, Y. Zhang, H.-J. Kim, S. Choi, and Z. Lochner, “Growth and fabrication of high-performance GaN-based ultraviolet avalanche photodiodes,” *J. Cryst. Growth*, vol. 310, no. 23, pp. 5217–5222, Nov. 2008.

[13] J. C. Carrano, D. J. H. Lambert, C. J. Eiting, C. J. Collins, T. Li, S. Wang, B. Yang, A. L. Beck, R. D. Dupuis, and J. C. Campbell, “GaN avalanche photodiodes,” *Appl. Phys. Lett.*, vol. 76, no. 7, pp. 924–926, Feb. 2000.

[14] M. Moresco, F. Bertazzi, and E. Bellotti, “Theory of high field carrier transport and impact ionization in wurtzite GaN. Part II: Application to avalanche photodetectors,” *J. Appl. Phys.*, vol. 106, no. 6, p. 063719, Sept. 2009.

[15] F. Ma, S. Wang, X. Li, K. A. Anselm, X. G. Zheng, A. L. Holmes, and J. C. Campbell, “Monte carlo simulation of low-noise avalanche photodiodes with heterojunctions,” *J. Appl. Phys.*, vol. 92, no. 8, pp. 4791–4795, Oct. 2002.

[16] N. Duan, S. Wang, X. G. Zheng, X. Li, N. Li, J. C. Campbell, C. Wang, and L. A. Coldren, “Detrimental effect of impact ionization in the absorption region on the frequency response and excess noise performance of InGaAs-InAlAs SACM avalanche photodiodes,” *IEEE J. Quantum Electron.*, vol. 41, no. 4, pp. 568–572, Apr. 2005.