Energy balance modeling of Ge-on-Si waveguide avalanche photodetectors

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***Abstract*—Commercial CAD tools for carrier transport simulation in optoelectronic devices are commonly based on the drift-diffusion (DD) model. In the design of silicon photonics optical interconnects, the DD approach can be acceptable for p-i-n photodetectors, but may be inadequate for avalanche photodiodes (APDs). Here we discuss the DD limitations in the case of waveguide Ge-on-Si SACM APDs, and we investigate the advantages and shortcomings of higher-order descriptions, with particular attention to the energy balance model.**

The past few years have witnessed a renewed interest in Si photonics, a key-enabling technology for the integration of optical and electrical subsystems. Focusing our attention on waveguide photodetectors, which are fundamental components in optical interconnects, a common implementation consists of p-i-n devices [1], where the intrinsic absorption region is usually obtained by growing a Ge layer on a doped section of the Si waveguide. These devices can exhibit an electrooptical bandwidth in excess of 40 GHz [2]. An alternative solution is based on waveguide Ge-on-Si avalanche photodiodes (APDs), which are particularly interesting in applications where high sensitivity is required thanks to their internal gain [3]. The computer-aided design (CAD) of both p-i-n and avalanche detectors is often carried out by means of carrier transport simulators based on the drift-diffusion (DD) model [4]. Indeed, thanks to its conceptual simplicity and comparatively light computational burden, most semiconductor device CAD tools are based on this model. However, a modeling approach based on DD can be ill suited to APDs, and higher-order semiclassical descriptions [5] have been adopted both in Si-based devices [6] and in other materials systems [7], [8], [9]. A possible compromise between accuracy and computational complexity is represented by the energy balance model (EB) [10], [11]. With EB it is possible to overcome the local relations which govern the transport phenomena in the DD picture, since carrier velocities and impact ionization coefficients become functions of the electron and hole energy (temperature) and not just of the electric field. Critical parameters for the EB description are the electron and hole energy relaxation times, which can be derived from experiments or Monte Carlo simulations [12].

In this work we explore the possibility to perform EB simulations of the Ge-on-Si separate absorption and charge multiplication (SACM) APD presented in [13], [14], using the Sentaurus Device numerical simulator by Synopsys [15]. The material parameters adopted in the simulations are reported in Table I. The preliminary investigations presented here are

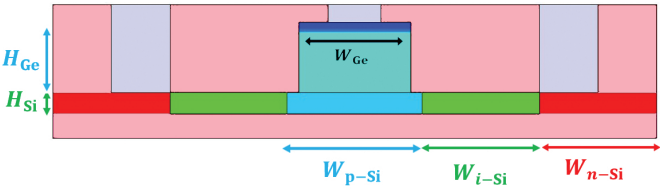

Fig. 1. 2D cross-section of the SACM APD under simulation, where $H_{\mathrm{Ge}} = 0.60\,\mu$m, $H_{\mathrm{Si}} = 0.18\,\mu$m, $H_{\mathrm{W}} = 0.75\,\mu$m, $W_{\mathrm{i-Si}} = 1\,\mu$m, $W_{\mathrm{n-Si}} = 1\,\mu$m, $W_{\mathrm{p-Si}} = 1.15\,\mu$m.

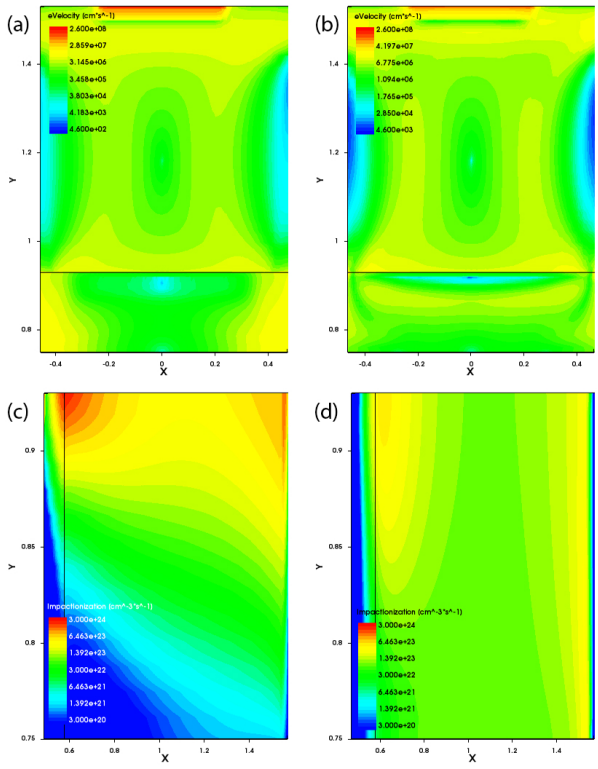

Fig. 2. Electron velocity v_n in the Ge absorber from (a) DD and (b) EB simulations; cumulative impact ionization rate G_{ii} in the Si multiplication region from (c) DD and (d) EB models.

TABLE I
MATERIAL PARAMETERS OF SI AND GE USED IN THE SIMULATIONS [15].

Parameter	Si		Ge	
E_g (eV)	1.12416		0.6638	
ϵ	11.7		16.2	
χ (eV)	4.0727		4.0	
	n	p	n	p
μ_0, cm^2/s/V	1417	470.5	3900	1900
μ_{exp}	2.5	2.2	1.6	2.3
$\beta_{0,DD}$	1.109	1.213	1.109	1.213
$v_{sat,0}$, $10^7\ cm/s$	1.0700	0.837	0.743	0.743
τ_c, s	0.3	0.25	0.3	0.25

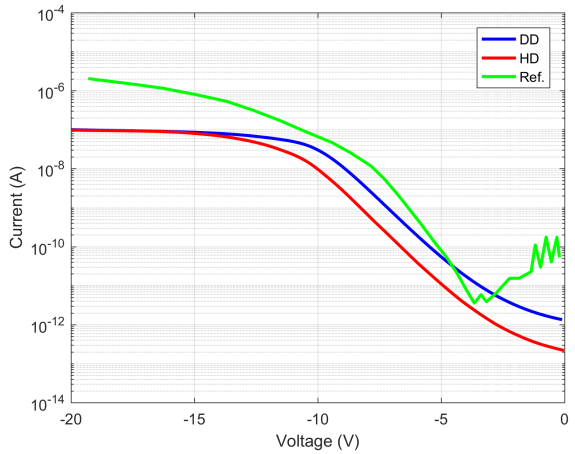

Fig. 3. Comparison of theoretical and experimental [14] $I(V)$ characteristics of the SACM APD under illumination.

limited to the 2D device cross-section (Fig. 1), used as a test bench for model validation and calibration; future works will consider the full 3D geometry of the waveguide detector. The high-field mobility model by Canali [16] describing velocity saturation has been employed both in Si and Ge, while impact ionization in the Si multiplication region has been included by means of the van Overstraeten - de Man model [17].

Simulations under illumination have been carried out by assuming a uniform optical generation rate $G_{opt} = 10^{24}\text{cm}^{-3}$ in the Ge absorber region. Looking at the 2D maps reported in Fig. 2, we can observe that the electron velocity v_n in the absorber region predicted by DD is lower and has a more uniform distribution when compared to EB; on the other hand, the impact ionization rate G_{ii} is less localized in the EB scenario than with DD. Fig. 3 shows the current-voltage $I(V)$ characteristics under illumination obtained with the DD and EB models. The two descriptions predict similar trends, but the photogenerated current is smaller with EB. Comparing the simulated $I(V)$ curves with the experimental results from [14], the need for the inclusion of tunnelling and/or trap-assisted processes, not taken into account in the present simulations and probably enhanced in Ge-on-Si devices because of the high density of defects in the region of the Si-Ge interface, is apparent from the differences observed at low bias. Contrary to experiments, in both models impact ionization becomes significant at a reverse bias larger than 20 V, suggesting that the standard impact ionization parameters for Si and Ge should be probably reassessed for this class of devices.

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