Simulation Study of the Origin of Ge High Speed Photodetector Degradation

B. Arunachalam, J.-E. Broquin, Quentin Rafhay, D. Roy, A. Kaminski

Simulation study of the origin of Ge High Speed Photodetector degradation

B. Arunachalam, Q. Rafhay, A. Kaminski, J.-E. Broquin
Université Grenoble Alpes, CNRS, Grenoble INP, IMEP-LAHC, 38000 Grenoble, France, Université Savoie Mont Blanc, IMEP-LAHC, 74000 Annecy, France
balraj.arunachalam@grenoble-inp.fr

D. Roy
[1]STMicroelectronics, 850 rue Jean Monnet, 38926 Crolles cedex, France

***Abstract*—The reliability of Si photonics and optoelectronics devices is emerging as a major new topic. By using TCAD simulations, this work investigates the microscopic origins of the Ge High Speed Photodetector (HSPD) performance losses during stress obtained in [1]. It confirms the key roles of the carrier lifetime degradation on both dark current increase and photonics current decrease, which could be triggered by surface recombination (SR), especially at the Buried Oxide (BOX). Other sources of degradation are studied, as fixed charges in the SiO_2 passivation layer and interface state (D_{it}).**

I. INTRODUCTION

Optoelectronic devices are one of the building blocks of optical telecommunications and Si photonics. Up to now, the only reliability protocols for telecom applications are the Telcordia ones [2], which implies very long pass/fail test (2000h). As no physical understanding of the degradation of Si photonics devices has been reached yet, these tests are still the reference one. [1] and [3] have however recently experimentally demonstrated that HSPD are prone to significant dark current and responsivity degradation with voltage stresses and temperature. Using a simple model, these degradations have been attributed in [1] to degradation of the carrier lifetime, inducing strong carrier recombination. The aim of this work is to investigate the HSPD reliability using Sentaurus TCAD. The impact of carrier lifetime (τ) will be at first studied, followed by the roles of different transport mechanisms, which could occur in these p-i-n diodes. The influence of SR on the I_{dark} will be detailed. Finally, other sources of degradation like fixed charges and D_{it} will be included.

II. IMPACT OF CARRIER LIFETIME

The studied device is built on a SOI wafer, whose Si film is etched to form optical waveguide, along which the HSPD is placed [4]. The Transmission electron microscopy (TEM) image of the HSPD is given in fig. 1. In fig 2 are given the two architectures studied in this work. A first simple pseudo 1D structure is studied to match the 1D model of [1]. The second 2D structure is designed to mimic the geometry of fig. 1. The optical generation rate is constant in the whole device and equal to $6.75 \cdot 10^{25}$ $cm^{-3}s^{-1}$. The results obtained in [1] will be checked at first on the pseudo 1D structure including only SRH recombination. By varying the carrier lifetime τ, dark I-V (fig. 3) and illuminated (fig. 5) characteristics are obtained. It can be seen that the dark current increases with decrease in τ, due to the increase of carrier recombination, or equivalently, the decrease of carrier diffusion length (fig. 4). The raw illuminated I-V curves are less straight forward to interpret (fig. 5). The decrease of τ induces at first a decrease of the light current, which then increases again for very small τ (fig. 6). However, the responsivity is function of the photonics current defined by $I_{phot} = I_{light} - I_{dark}$. When plotting I_{phot} vs τ (fig 6) the trend is monotonic and fully confirms the results obtained in [1].

III. TRANSPORT MECANISMS AND RECOMBINAISONS

The impact of different transport mechanisms is shown in fig. 7, where SRH dominated I_{dark} is compared to the SRH / Band-To-Band (BTB) and BTB / Trap Assisted Tunneling (TAT). In Sentaurus, TAT is treated as a field enhancement of SRH [5], which explains the common trends at low voltage. High voltages are always dominated by BTB. On fig. 8 is compared the pseudo 1D and 2D structure, showing a strong increase of I_{dark} with geometric variation. All other simulations have been carried out with the 2D structure. On fig. 9 is added the impact of the SR at the interface of a surrounding passivation layer (fig. 11(a)). It can be seen that the increase of the surface recombination velocity (SRV) leads to increase of I_{dark}, as in the case of the decrease of τ. When excluding all other recombination, variation of SRV from 0 to 10^7 cm/s can give variation of current over 6 orders of magnitude (fig. 10). SR can therefore explain the degradation of I_{dark} obtained in [1]. On fig. 12 is compared different placement of SR, either all around the device (fig. 11(a)), or only on top (fig. 11(b)). This shows that the top part plays a marginal role, and that the BOX section leads to significant degradation, highlighting the necessity to correctly passivate this interface.

IV. OTHER SOURCES OF DEGRADATION

Other sources of potential degradation have been included in the simulation to estimate their impact: negative (fig. 13) and positive (fig. 14) fixed charge in a surrounding oxide, its impact on different transport mechanisms (fig. 15), the role of its placement (fig. 16 and 17) and interface states (fig. 18). None of them has been found to significantly degrade the dark current.

V. CONCLUSIONS

These simulation results hence confirm that the dark current and photonic current degradation observed in [1] are indeed explained by lifetime collapse during stress, potentially triggered by the increase of surface recombination. They imply that great care should be taken with the passivation of the encapsulation layers, especially at the bottom of the device. Additional experimental work will be required in the future to study the dynamic increase of surface recombination.

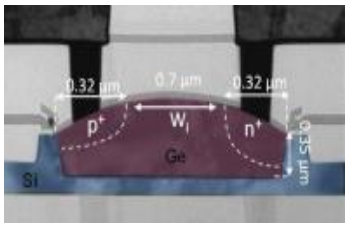

Fig. 1: TEM of the HSPD.
$N_d = 6{\cdot}10^{18}$ cm^{-3}, $N_a = 3{\cdot}10^{19}$ cm^{-3}

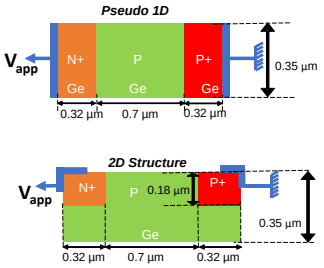

Fig. 2: Simulated geometries of the pseudo 1D and 2D structure.

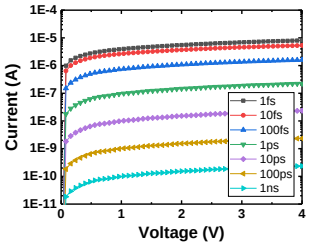

Fig. 3: I_{dark} vs V for different lifetime of the Ge.

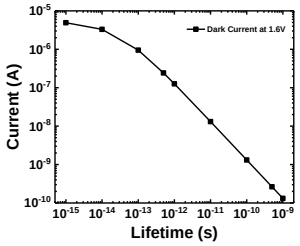

Fig. 4: I_{dark} vs τ reproducing the degradation observed in [1]

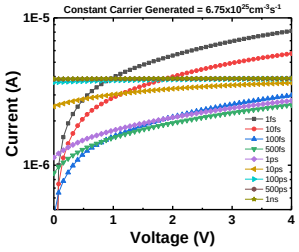

Fig. 5: I_{light} vs V for different τ for a constant optical generation rate in the HSPD

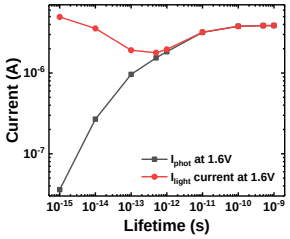

Fig. 6: I_{light} and I_{phot} vs τ showing that a strong part of I_{light} is due to I_{dark} for very small τ

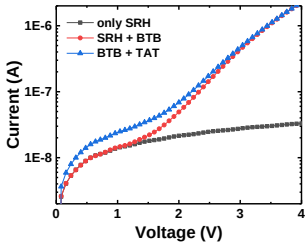

Fig. 7: Impact of different transport mechanisms on the I-V of the pseudo 1D geometry

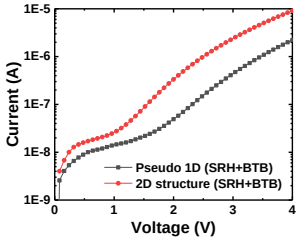

Fig. 8: Impact of the geometry on the I_{dark} of the HSPD

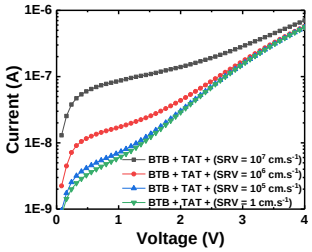

Fig. 9: I_{dark} vs V including all mechanisms for different values of SRV (2D geometry)

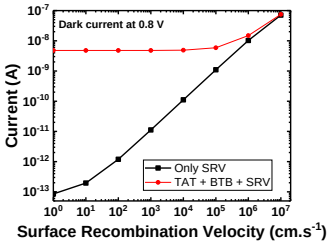

Fig. 10: Increase of I_{dark} with SRV when excluding all mechanisms, or including them

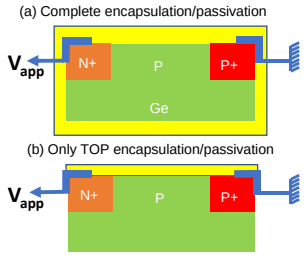

Fig. 11: Scheme of the SRV placement (a) all around or (b) only at the top

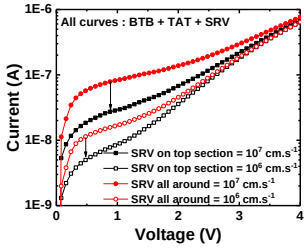

Fig. 12: I_{dark} vs V for different placement of the SRV (fig. 11) and two values of SRV.

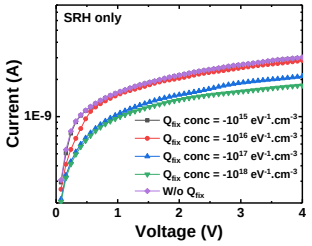

Fig. 13: I_{dark} vs V for different concentration of negative Q_{fix}

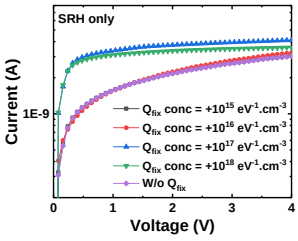

Fig. 14: I_{dark} vs V for different concentration of positive Q_{fix}

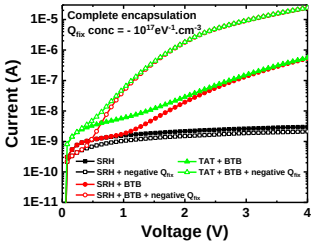

Fig. 15: Impact of Q_{fix} on the I_{dark} vs V including different transport mechanisms

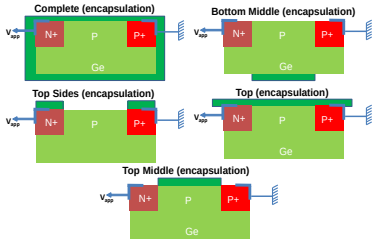

Fig. 16: Scheme of the Q_{fix} placement around the device

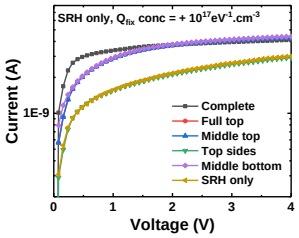

Fig. 17: Impact of the Q_{fix} placement around the device on I_{dark}

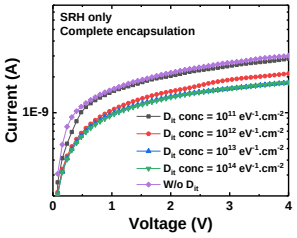

Fig. 18: I_{dark} vs V for different interface state densities

References:

[1] F. Sy *et al*, IEEE IRPS 2019

[2] TELCORDIA GR-468-CORE Generic Reliability Assurance Requirements for Optoelectronic Devices Used in Telecommunication Equipment

[3] A. Leśniewska *et al*., IEEE IRPS 2019 [4] F. Boeuf *et al.*, IEEE IEDM 2013

[5] Sentaurus™ Device User, 2019, Sentaurus version used: 2016

Acknowledgements:

This work has been founded by the ICPEI Nano2022 FiabPhSi project