# Modeling the Effects of Interface Traps on Passive Quenching of a Ge/Si Geiger Mode Avalanche Photodiode

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*Abstract*—**The influence of interface donor and acceptor traps on the behavior of Ge/Si separate absorption, charge and multiplication (SACM) Geiger mode avalanche photodiodes (GM-APDs) under passive quenching is modeled. The effects of different trap types on the quenching behavior are investigated in this paper for the first time. Our results show that trap type and trap density significantly influence the APD quenching time and ability to quench for a particular quenching resistor.**

*Index Terms*—**Avalanche photodiode (APD), Geiger mode (GM), germanium, passive quenching, interface trap, silicon**

## I. INTRODUCTION

Near infrared (NIR) avalanche photodiodes (APDs) operated in Geiger mode (GM) are used for a number of single photon applications including time resolved spectroscopy, quantum key distribution (QKD), and single photon sources. Increased bit rates are highly desired for applications such as QKD, however, speeds are limited by dark counts due to traps in the material that charge during the GM pulse and subsequently detrap. Long wait times are typically required after every pulse to allow traps to discharge. Reduction in charge traps would be a promising path to increasing the quantum bit rate. Significantly fewer charge traps have been observed in materials such as silicon. Incorporating a silicon avalanche region with a germanium absorption region offers a potential path to improving NIR GM detection frequencies [1]. However, the influence on GM performance of traps at the interface between the Si and the Ge has not yet been investigated.

Typically Ge/Si GM-APDs and photodiodes can be fabricated either by epitaxial growth of Ge on Si or by wafer bonding. With epitaxy it is difficult to obtain a high quality Ge layer with sufficient thickness for high absorption because of the 4% mismatch in the lattice constants of Ge and Si [2]. A drawback of wafer bonding can be the formation of a Ge native oxide at the Ge/Si interface [2]. In each case the electrical and optical characteristics of the APDs are strongly influenced by the heterojunction interface properties, particularly the density of interface traps created by the defects and dislocations caused by relaxation of Ge on Si and/or by the dangling bonds of the Ge native oxide. Experimental and theoretical research reveals that upon exposure of a clean Ge surface to oxygen, a number of defect structures are created, including dangling bonds. It is predicted that the dangling bond states are both located in the lower part of the Ge gap centered at energies $E_{acc} = E_v + 0.11$ eV with charge transition neutral/negative and $E_{don} = E_v + 0.05$ eV with charge transition positive/neutral for acceptor and donor interface traps, respectively [3], where $E_v$ is the valence band edge. Fig. 1 shows the acceptor and donor trap centers.

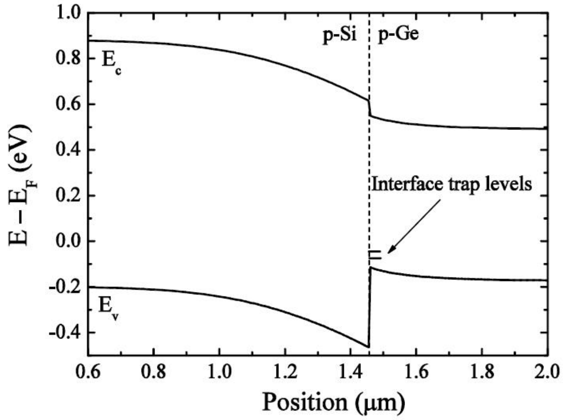

Fig. 1. Band diagram and defect levels at p-Si/p-Ge interface at equilibrium (doping concentration is $5\times10^{15}$ cm$^{-3}$ for Si and Ge).

The effects of these interface traps on the characteristics of Ge/Si Geiger Mode APDs under passive quenching based on the drift-diffusion model using the Silvaco TCAD tool are presented here.

## II. DEVICE STRUCTURE AND PHYSICS OF THE MODEL

Fig. 2 shows the schematic configuration of the Ge/Si SACM-APD [4].

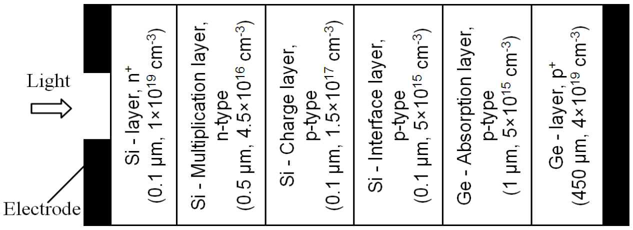

Fig. 2. Schematic of the Ge/Si SACM-APD structure modelled in this work.

The Ge/Si APD is modeled by solving the Poisson's equation coupled with the charge continuity equations. Trap centers exchange charge with the conduction and valence bands through the emission and capture of carriers. In the time domain the acceptor and donor traps do not reach equilibrium

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instantaneously but require time for electrons to be emitted or captured so trap rate equations are applied.

## III. SIMULATION RESULTS AND DISCUSSIONS

Mixed-mode transient simulations were implemented for the circuit in figure 3. The quench resistor was set at 150K. $V_{bias}$ was first ramped to 4V above breakdown with impact ionization switched off. A transient simulation was then run implementing Selberherr's impact ionization model and Shockley-Read-Hall (SRH) recombination. A light pulse was switched on every 1µs to instigated GM breakdown.

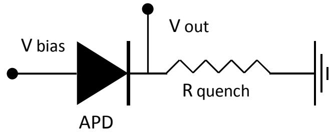

Fig. 3. Passive Quenching Circuit for mixed mode transient simulations.

Figure 4 shows one breakdown event each for acceptor trap densities 1 x $10^{11}$ $cm^{-2}$, 8 x $10^{11}$ $cm^{-2}$ and 5 x $10^{12}$ $cm^{-2}$. The inset shows three consecutive breakdown events for acceptor traps with density 1 x $10^{11}$ $cm^{-2}$. We do not show the donor trap plots here since they follow the response of the lower density acceptor response closely. The plots demonstrate a significant difference in Geiger Mode response depending on the trap type and density. Note that for the case with trap density 8 x $10^{11}$ $cm^{-2}$ $V_{out}$ settles at -7.5 V and the APD does not quench.

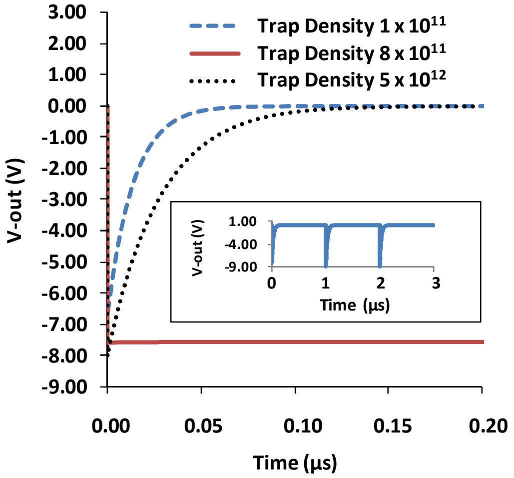

Fig. 4. Transient plot of passive quenching for acceptor traps. Inset shows three consecutive breakdown events for acceptor traps with density 1 x $10^{11}$ $cm^{-2}$.

Figure 5 shows the electric field profile in the APD at different times during the breakdown event for acceptor trap density 1 x $10^{11}$ $cm^{-2}$. As expected the electric field drops from its peak value until the avalanche is quenched before it gradually rises to its original level. Figure 6 shows the recombination rate for three acceptor trap densities 4 x $10^{-9}$ seconds after the breakdown begins. For trap density 8 x $10^{11}$ $cm^{-2}$ the recombination rate goes positive (> 1 x $10^{18}$ $scm^{-3}$) in the multiplication region. This correlates with figure 4 which shows that in this case the APD does not quench.

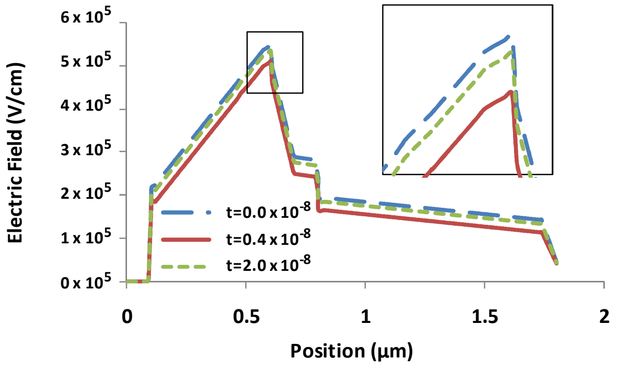

Fig. 5. Electric field profile at three time points during a breakdown event for an APD with acceptor trap density 1 x $10^{11}$ $cm^{-2}$. Inset is close up of peak field.

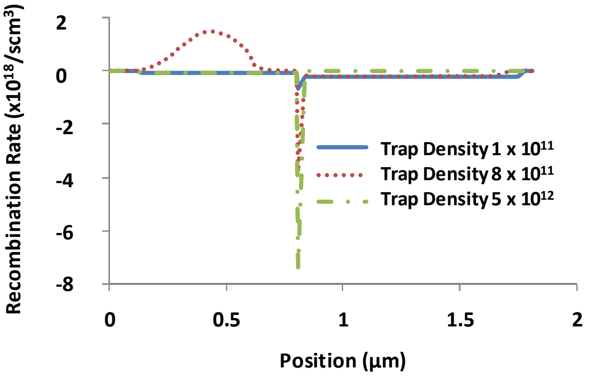

Fig. 6. Recombination rate for three acceptor trap densities at 4 x $10^{-9}$ seconds after the breakdown begins.

## IV. CONCLUSIONS

In this paper the effects of different trap types on passive quenching behaviour of a Ge-Si Geiger Mode APD are investigated for the first time. Our results indicate that trap type and trap density significantly influence the APD quenching time and ability to quench for a particular quenching resistor.

## ACKNOWLEDGEMENTS

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