Monte Carlo modelling of Ge/Si single-photon detectors

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BACKGROUND

Various devices are available for detection of very low amplitude optical signals, down to single photons [1]. One which has become popular and increasingly widespread in recent years is the single photon avalanche diode (SPAD), which is essentially an avalanche photodiode (APD) operating in a Geiger (trigger-reset) mode. The numerous existing Si SPAD designs all benefit from the infrastructure surrounding this material and the potential for integration with driver electronics (CMOS). However, due to the limited optical properties of Si, III-V material SPADs have also found commercial application, enabling operation at longer wavelengths yet often requiring low temperatures in order to minimise dark count rates [2].

III-V SPADs commonly contain heterostructures, where the absorption and multiplication behaviour required in the device is spatially separated, allowing each to be individually optimised [2]. To capitalise upon the benefits of a Si-compatible material system yet allow operation at 1.55 μm, we are developing SPAD designs based on a Ge/Si heterostructure.

One drawback arising from combining multiple materials lies with the difficulty of efficiently transporting optically-generated charge across the heterointerface [3]. Since this can lead to delayed transport and could significantly reduce sensitivity due to charge recombination or trapping, we apply a charge transport model to determine key device parameters and the consequences for design of efficient SPADs.

STRUCTURE & MODELLING

The initial structure considered is a p-i-p-i-n design, as per Fig. 1. The device operates under a heavy reverse bias, with the central charge layer allowing the electric fields in the absorption and multiplication regions to be shifted relative to one another. Prior to optical absorption the structure is essentially empty of mobile charge throughout the active layers, so it is assumed that only once charge enters the Si layer does the number of charge carriers increase significantly beyond the initial photo-generated pair. Consequently, to isolate heterojunction transfer effects, the model currently includes only the lightly-strained [4] Ge absorption layer, with a static electric field profile arising from the finite background doping. Since the p-i-p-i-n design relies on electron-initiated impact-ionization, we apply an established ensemble Monte Carlo transport code [5,6] where electron dynamics are modelled via an analytical band-structure which allows for non-parabolicity and elliptical energy surfaces when appropriate. Established transport parameters [7] are supplemented by deformation potentials for Γ-L and Γ-X electron-phonon scattering determined from optical measurements [8], due to initial generation of electrons in the Γ minima.

Through tracking ensemble statistics, from initial charge generation to minima- and energy-dependent transmission over the heterointerface, parameters limiting device performance have been identified. These include dopant type and density in both Ge absorber and Si charge layers, due respectively to their influence on electron energy distributions and their potential effect upon tunnelling across the interface (Fig. 2, 3).

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REFERENCES

[1] G. S. Buller and R. J. Collins, *Single-photon generation and detection*, Meas. Sci. Technol. **21**, 012002 (2010).

[2] S. Pellegrini et al, *Design and performance of an InGaAs-InP single-photon avalanche diode detector*, IEEE J. Quantum Electron. **42**, 397 (2006).

[3] S. R. Forrest, O. K. Kim and R. G. Smith, *Optical response time of $In_{0.5}Ga_{0.47}As/InP$ avalanche photodiodes*, Appl. Phys. Lett. **41**, 95 (1982).

[4] V. A. Shah, A. Dobbie, M. Myronov and D. R. Leadley, *High quality relaxed Ge layers grown directly on a Si(001) substrate*, Solid-State Electron. **62**, 189 (2011).

[5] N. J. Pilgrim, A. Khalid, G. M. Dunn and D. R. S. Cumming, *Gunn oscillations in planar heterostructure diodes*, Semicond. Sci. Tech. **23**, 075013 (2008).

[6] T. Sadi, R. W. Kelsall and N. J. Pilgrim, *Electrothermal Monte Carlo Simulation of Submicrometer Si/SiGe MODFETs*, IEEE T. Electron Dev. **54**, 332 (2007).

[7] C. Jacoboni, F. Nava, C. Canali and G. Ottavani, *Electron drift velocity and diffusivity in germanium*, Phys. Rev. B **24**, 1014 (1981).

[8] G. H. Li, A. R. Goñi, K. Syassen and M. Cardona, *Intervalley scattering potentials of Ge from direct exciton absorption under pressure*, Phys. Rev. B **49**, 8017 (1994).

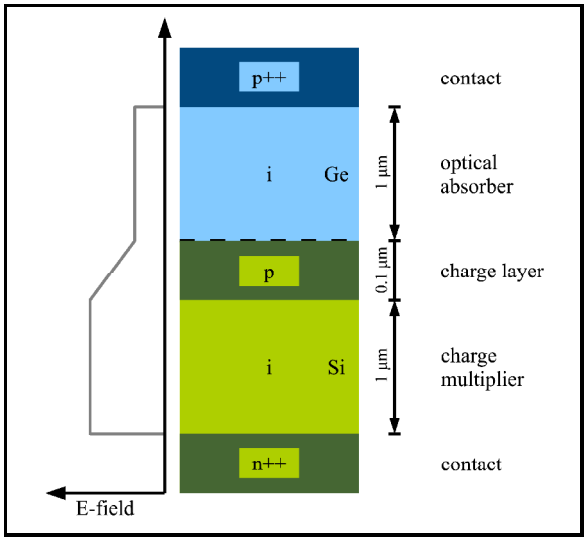

Fig. 1. Schematic of p-i-p-i-n layer structure and idealised electric-field profile; various finite dopant densities in the Ge optical absorber layer are considered in the analysis.

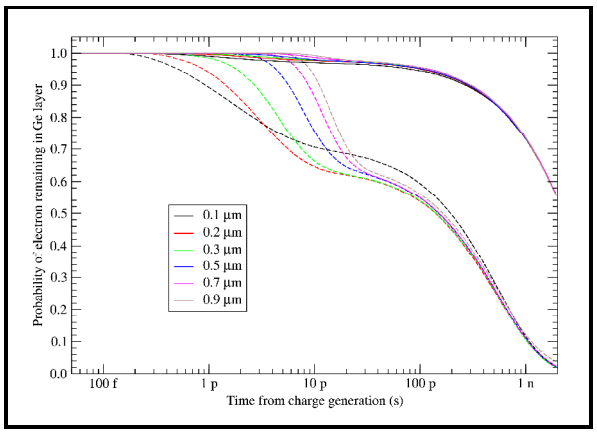

Fig. 2. Probability of electron remaining in Ge absorption layer as a function of time after generation at a fixed distance from Ge/Si heterointerface (see legend). Background dopant density is ~10^{15} cm^{-3}. Device is assumed reverse-biased such that absorption layer is just fully depleted, ie. electric field ranges from zero to 10^6 V/m. Dopant type significantly affects transport timescales: compare p-type dopants (dashed) and n-type dopants (solid).

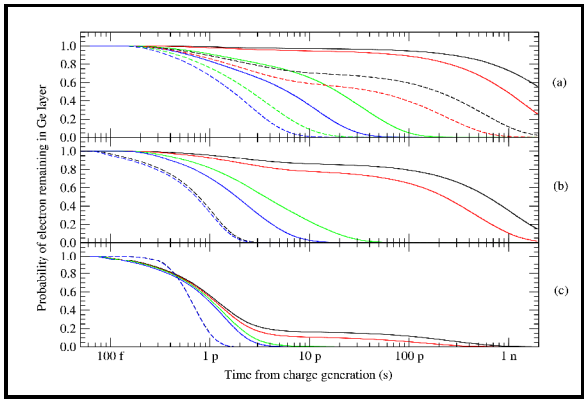

Fig. 3. Probability of electron remaining in Ge absorption layer as a function of time after generation 0.1 µm from Ge/Si interface, for doping densities of (a) ~10^{15} cm^{-3}, (b) ~10^{16} cm^{-3}, (c) ~10^{17} cm^{-3}. Device is assumed reverse-biased as per Fig. 2, ie. electric field ranging linearly from zero to a particular peak field. Ge dopant type is again important: compare p-type (dashed) and n-type (solid). Black lines represent inclusion of only thermionic transmission over the heterointerface, as in Fig. 2, whereas red/green/blue curves represent the addition of tunnelling transport across the heterointerface for increasing electric fields in the Si charge layer, corresponding to densities of 10^{17} cm^{-3}, 5 x 10^{17} cm^{-3} and 10^{18} cm^{-3} respectively.