Calculation of Band-to-band Tunnelling Currents in Germanium

H.M. Rafferty, R.W. Kelsall and Z. Ikonic
Institute of Microwaves and Photonics, School of Electronic and Electrical Engineering, University of Leeds, Woodhouse Lane, Leeds, LS2 9JT, UK
e-mail: r.w.kelsall@leeds.ac.uk

INTRODUCTION

Ge-on-Si single-photon avalanche detectors (SPADs) are useful in number of photonics systems. Their principal mode of operation involves electron-hole pair generation in the Ge 'absorption' region, and carrier drift into the high-field Si 'multiplication' region. Whilst the electric field in the Si layer must be sufficiently high to promote impact ionisation, a high field in the Ge leads to increased noise and dark current. One cause of field-induced dark counts in Ge is Zener (1), or band-to-band tunnelling. In this work, band-to-band tunnelling currents in bulk germanium have been calculated.

MODEL

Band-to-band tunnelling currents were calculated using an empirical pseudopotential method and a complex bandstructure matching technique for a multilayer structure.

Complex band structure describes all (or a number of) electron states in bulk, which behave exponentially in a particular direction, with a real wave vector of states (propagating states, some of which have energies in the allowed bands), or with a complex wave vector (evanescent states, e.g. all those with energies in the band gap). When a propagating state comes to a multilayer structure, it 'excites' various propagating and evanescent states inside the next layer, and the process continues until some number of propagating state(s) at the exit form a tunnelling current. In the plane-wave representation, the wavefunction matching at interfaces between layers is done by using the continuity of each in-plane harmonic of the full wavefunction.

For the one-dimensional case considered here, states are classified as forward or backward, depending on their current (if propagating) or the direction of decay (if evanescent), with co-efficients in these directions given by a and b, respectively. Though the real potential in a biased bulk Ge is continuous, the simulation considers discretized sections of material with a step-size determined by convergence calibration; each step is set at a potential offset relative to the previous step. Matching between states in the *nth* and *n+1th* step is given by an interface matrix, *I*:

$$\begin{bmatrix} a_{n+1} \\ b_{n+1} \end{bmatrix} = I(n, n+1) \begin{bmatrix} a_n \\ b_n \end{bmatrix} \qquad (1)$$

and together with the exponential propagation matrix across a layer, this is used to construct the scattering matrix *S* for the whole structure

$$\begin{bmatrix} a_n \\ b_0 \end{bmatrix} = S(0, n) \begin{bmatrix} a_0 \\ b_n \end{bmatrix} \qquad (2)$$

and the transmission and reflection co-efficients determined from it. Following the calculation of one-dimensional transmission co-efficients across a range of energies in the band structure, and across a grid of in-plane wave vectors, the total tunnelling current may be calculated (3).

Tunnelling currents have been calculated for a range of bias conditions. The dependence of the tunnelling current on the thickness of the germanium has been investigated, and the relative contributions of different interband transitions (heavy or light hole to Γ or X conduction band states) have been identified.

ACKNOWLEDGMENT

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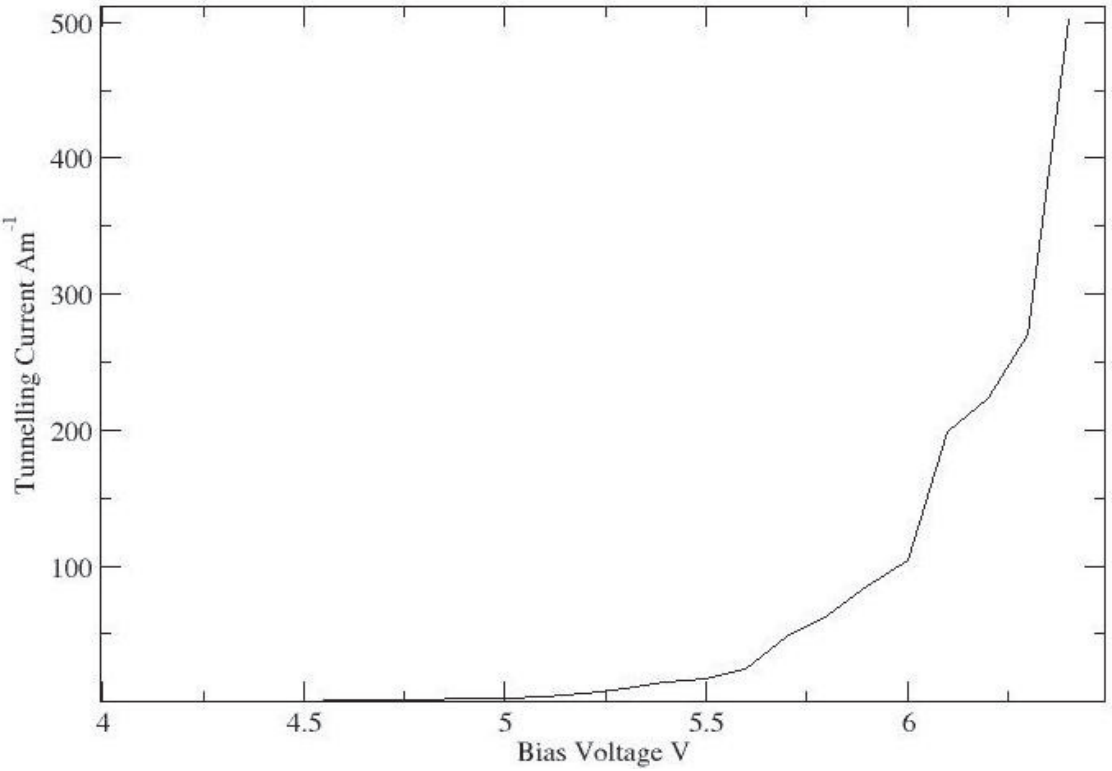

Fig. **1**. Band-to-band tunnelling current for a 0.2μm section of bulk Ge, under a range of bias voltages

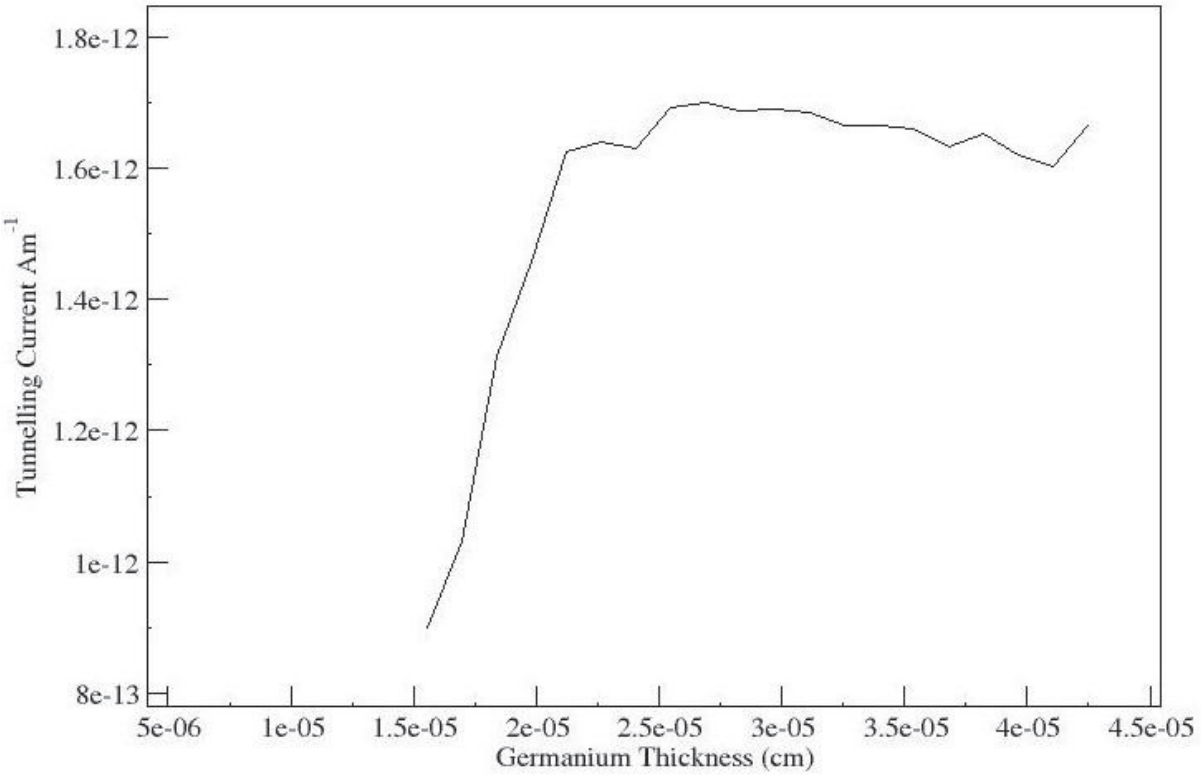

Fig. 2. Band-to-band tunnelling current for varying thicknesses of bulk Ge, under a 1.5V bias.