Band-to-Band Tunneling in 3D Devices

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INTRODUCTION

Tunneling devices have shown clear promise in providing a steep subthreshold swing, garnering much interest for ultra low power switching applications. In order to study the tunneling in realistic devices, it is necessary to consider a full 3D approach. In this work we utilise a recently proposed method [1] to compute band-to-band tunneling currents in 3D structures.

BAND-TO-BAND TUNNELING

Band-to-band tunneling is a complex mechanism and challenging to model accurately. Recently we presented a 3D approach for wave function propagation in direct semiconductors [1]. The developed method computes an effective tunneling barrier of arbitrary shape and varying effective mass. Injecting eigenmodes are calculated at contacts, and a propagating wave function is obtained. This model allows a study of a BTB tunneling barrier as it responds to changes in device geometry, material parameters and applied bias. The widely used WKB approach [2] calculates an estimated transmission coefficient (TC) from parameters that are extracted from the energy bands. Improvements to this approach have been suggested [3]. These methods, however, approximate the effective mass and extract linearized band parameters. WKB considers a single combined effective mass. However, the effect of the masses in valence and conduction bands may need to be considered in another manner, as their effect on tunneling may differ. The method discussed in this work does not make such WKB-like assumptions. A propagating wave is computed between the barriers using a QTBM-based approach. The effective mass and energy barrier is treated as a changing variable between the valence and conduction bands. This method computes the full wave tunneling through an effective barrier between the energy bands. 1D comparison with WKB approaches is demonstrated in Fig. 1, for an InAs p-n junction with symmetrical doping of $N_\mathrm{D}{=}1\times10^{19}\,\mathrm{cm}^{-3}$ and an applied bias of $V_G{=}{-0.1}\,\mathrm{V}$.

Computing BTB tunneling 1D removes consideration of geometry variation effects. This is an obvious challenge with 1D approximations of 3D behaviour. Our method, however, extends to 3D quite naturally. 1D barriers are replaced by full 3D energy barriers, and wave propagation is computed using a 3D QTBM-like approach.

SIMULATION RESULTS

In order to demonstrate the necessity for 3D analysis of tunneling in realistic devices a 30 nm InAs NW p-n junction is simulated. Symmetrical doping of $N_\mathrm{D}{=}1\times10^{19}\,\mathrm{cm}^{-3}$ and bias of $V_G{=}{-0.1}\,\mathrm{V}$ are applied, Fig. 2. NWs are not perfectly cylindrical structures, as was assumed in the previous simulation. Therefore, a tapered structure is created with a 30 nm diameter in the p-doped contact and a 10 nm diameter at the n-doped, Fig. 3. It must be noted here that 1D energy bands are quite similar between this and the device in Fig. 2. As such, 1D simulations would completely miss the effects of this device geometry. It is not only the physical dimensions of the device that must be considered. Doping geometries in tunneling devices may be complex and vary throughout the material. Here, we consider a doping variation radially through the NW device from Fig. 2. The doping is set to be largest at the surface and decrease towards the centre of the device, Fig. 4. Once again, the 1D band structure appears to be quite similar to the previously examined devices. Current was calculated for these devices at a few bias voltages. It is quite clearly shown that a significant change in current is experienced due to the 3D effect considerations.

DISCUSSION

This method provides a new insight into BTB tunneling in real devices, as the computation considers 3D variations in material properties (mass, doping), applied bias, or geometry. Th visualization of an effective BTB tunneling barrier allows for a better understanding of wave propagation. With this knowledge, tunneling device improvements and optimizations are possible.

ACKNOWLEDGMENT

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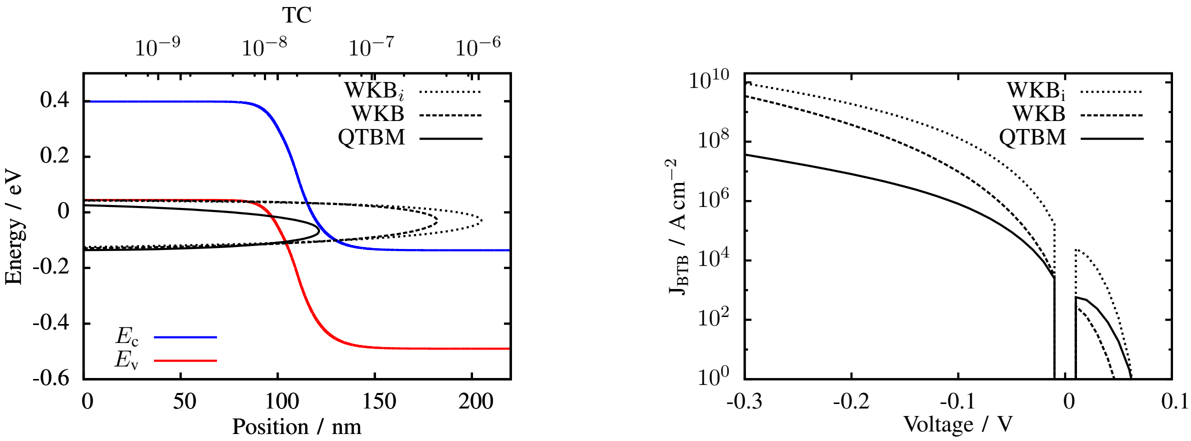
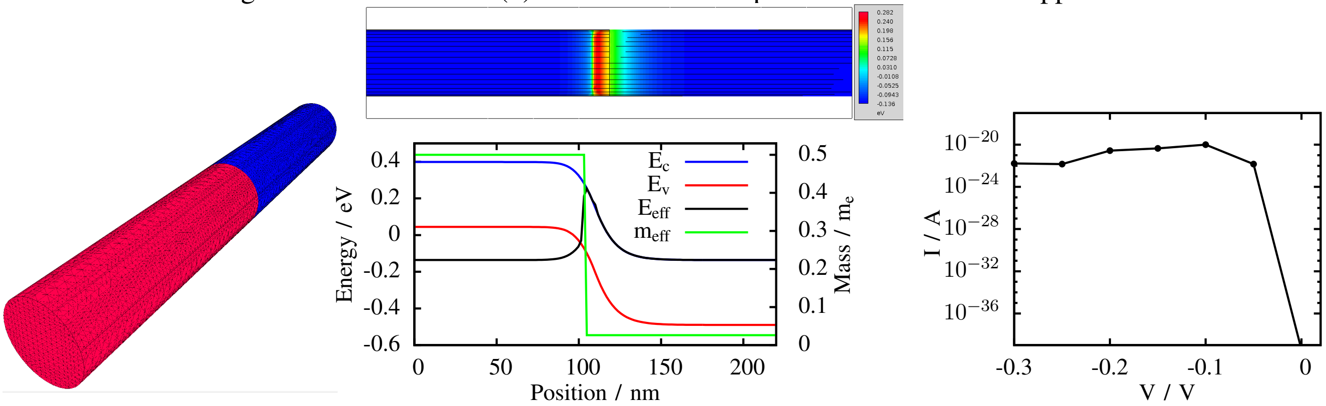


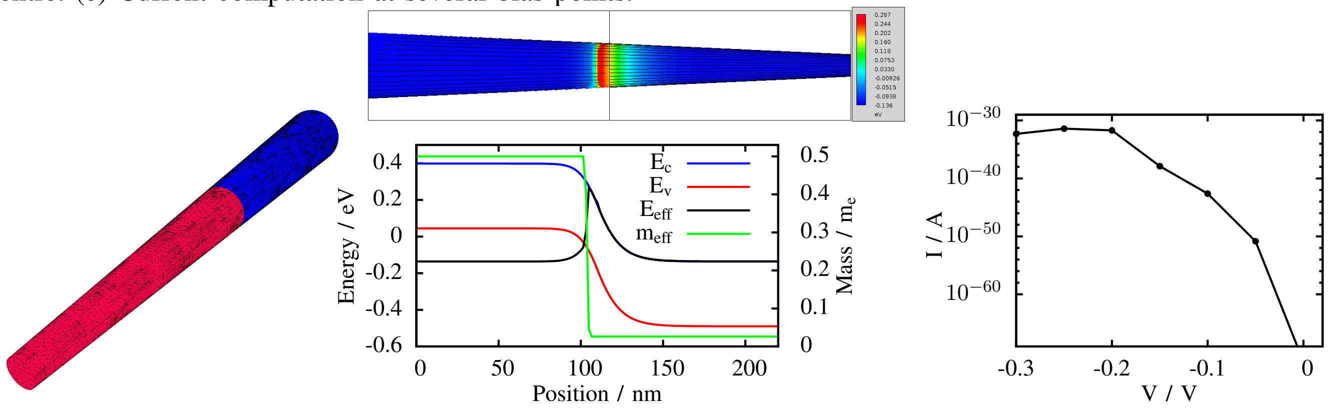
(a) (b)

Fig. 1: (a) Transmission coefficient changes with additional parameter considerations. WKB$_i$ considers only the tunneling length, WKB considers the variation in perpendicular energy contribution as well, QTBM considers those as well as change in effective mass. (b) BTB current comparison between these approaches



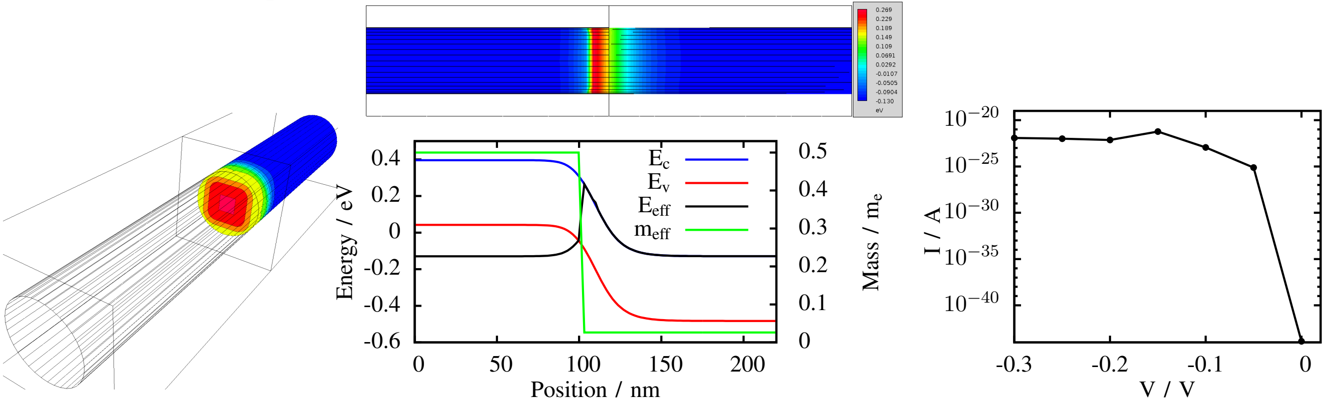
(a) (b) (c)

Fig. 2: (a) 3D InAs NW structure. (b) Effective tunneling barrier the middle of the bandgap, 1D cut through the centre. (c) Current computation at several bias points.



(a) (b) (c)

Fig. 3: (a) Modifed NW geometry. (b) Effective tunneling barrier the middle of the bandgap, 1D cut through the centre. (c) Current computation at several bias points.



(a) (b) (c) Current

Fig. 4: (a) 3D doping profile. (b) Effective tunneling barrier the middle of the bandgap, 1D cut through the centre. (c) Current computation at several bias points.