Multi-Dimensional Semiconductor Tunneling in Density-Gradient Theory

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Density-gradient (DG) theory has come into wide use as a physically well-founded approximate treatment of quantum confinement effects that is well suited for engineering-oriented applications including in multi-dimensions. DG theory has also been applied successfully to quantum mechanical tunneling [1], however, this application has received far less attention in part because it has been studied mostly in one dimension where direct quantum mechanical methods (e.g., using the Keldysh formalism) are a realistic alternative. At the last IWCE workshop I presented a DG treatment of multi-dimensional tunneling from ideal metals [2]. This research direction is continued here with a first DG analysis of direct, elastic tunneling from semiconductors in multi-dimensions.

The previous DG treatment of multi-dimensional tunneling from ideal metals [2] was simplified by the fact that, with the solution in the metal known, one could focus entirely on the electron transport in the barrier. The case of semiconductor tunneling is harder of course because one must analyze the transport in the semiconductors as well as in the barrier. In this regard, an important aspect of the approximate DG approach is its unified character: Essentially the same basic partial differential equations are applied inside the semiconductors and in the barrier, and these equations are solved simultaneously without involving eigenvalue problems or self-consistency iterations. The chief differences between the transport equations in the semiconductors and in the barrier arise from the relative importance of scattering. In the semiconductors the transport can be regarded as dominated by scattering so that the electron population tends to act as a single gas obeying a quantum-corrected drift-diffusion-like description, whereas in the barrier scattering is neglected ("elastic" tunneling) and, among other things, this implies that carrier populations emitted from different electrodes will not mix and must be treated separately. All of these features were present in the one-dimensional treatment presented in [1]. Also entirely analogous to the 1-D treatment are the boundary conditions, including the tunneling recombination velocity conditions [1] and the bandgap blocking effect depicted in Fig. 1 [3]. As in [2], the primary new ingredient in multi-dimensions enters through the steady-state continuity equation $\nabla\cdot(n\mathbf{v}_n) = 0$ that, unlike in one-dimension, cannot be integrated analytically. As a result, it becomes necessary to solve it for the velocity field in the barrier in order to find out where the electrons go, and obviously this equation must be solved simultaneously with the other governing equations. These equations, various useful transformations of them, and their numerical solution will all be given brief coverage in the presentation.

Although quantitative verification of the DG description of tunneling (and of descriptions of tunneling in devices generally) is an important topic [1-3], as a practical matter it tends not to be that critical because of the exponential dependence of the calculated tunneling currents on various physical parameters that are rarely known with much accuracy, e.g., the precise geometry, tunneling effective masses or barrier heights. For this reason, in this work the focus is on solutions of the DG equations, and on understanding their qualitative meaning and implications. As a first such solution, in Fig. 2 the importance of the bandgap blocking effect (Fig. 1) is explored in 1D by simulating a Si-SiO_2-Si tunnel diode with asymmetrical doping. As seen, the bandgap blocking effect is essential for getting the correct built-in voltage and the necessarily zero current at zero voltage (at least to good approximation). The kink seen near 0.1V is associated with the fact that for biases below the built-in voltage it is the forward current that is blocked by the bandgap. Representative conduction band and density profiles for the diode (with electron flow from left to right) are shown in Fig. 3; evident is the downstream depletion layer that, as it grows, causes the bandgap blocking effect to diminish with bias as seen in Fig. 2. Illustrating the use of the same DG equations (with bandgap blocking) in multi-dimensions, Fig. 4 shows a 2-D contour plot of the electron density in an n-channel SOI transistor with $V_{SD} = 0$ and $V_G = 0.5$V. This FET has a gate length of 50nm and an oxide thickness that varies from 3nm at the source and drain to 1.5nm at the center of the device (i.e., an "oxide smile"). In this plot as well as in the plots of current density in Figs. 5 and 6, the expected dominance of tunneling at the center where the oxide is thinnest is evident. These and other results illustrating the power and also the limitations of the DG approach for modeling devices that involve multi-dimensional semiconductor tunneling will be discussed in the presentation.

ACKNOWLEDGEMENT

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REFERENCES

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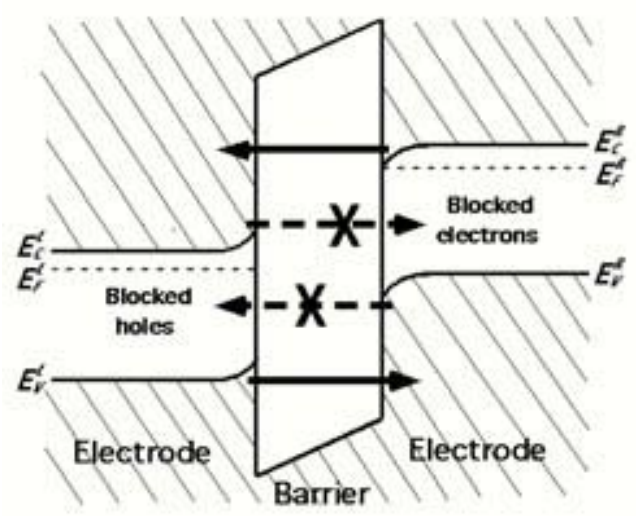

Fig. 1. Band diagram depicting the bandgap blocking effect in semiconductor tunneling.

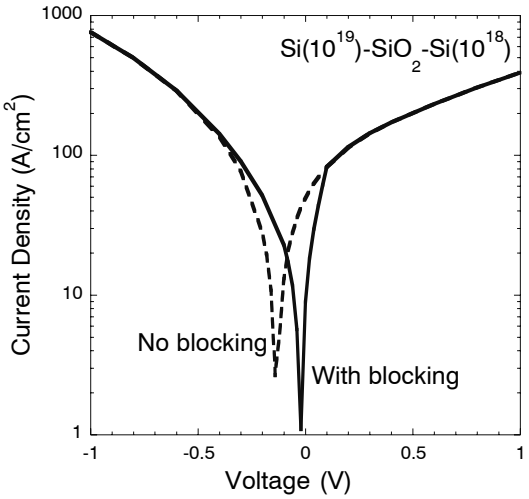

Fig. 2. Calculated J-V characteristic in an SIS diode showing the essential contribution of bandgap blocking at low voltage.

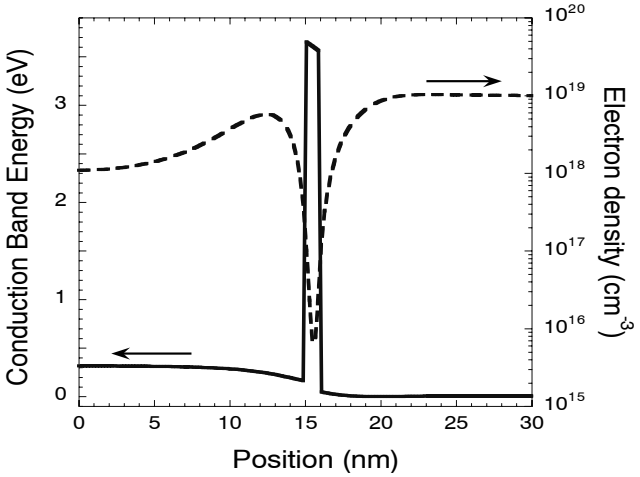

Fig. 3. Conduction band barrier and electron density in an asymmetrically doped SIS tunnel diode with V = -0.25V.

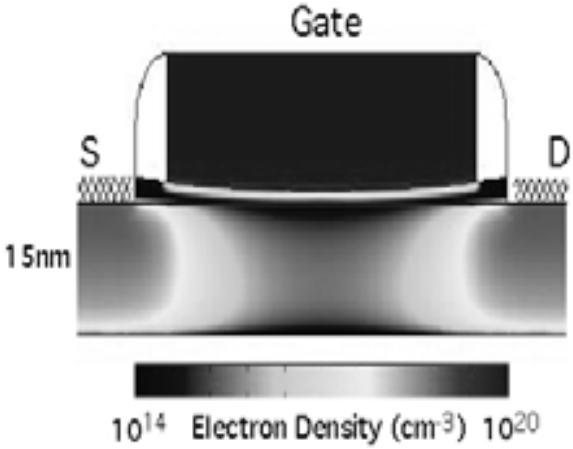

Fig. 4. Electron density contour plot in a 50nm gate length SOI FET with a non-uniform gate oxide.

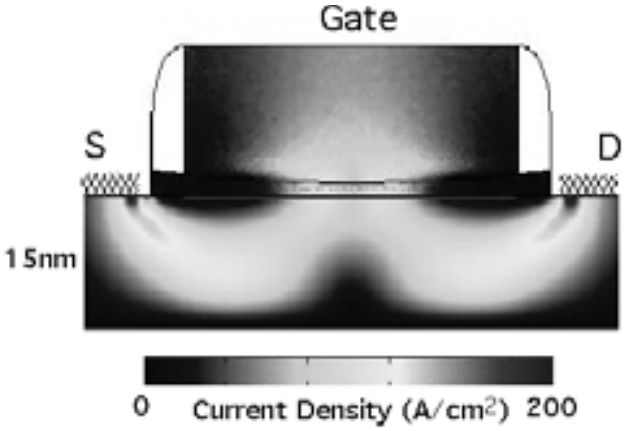

Fig. 5. Current density contour plot in a 50nm gate length n-channel SOI FET with a non-uniform gate oxide, V_G = -0.5 and V_{SD} = 0V.

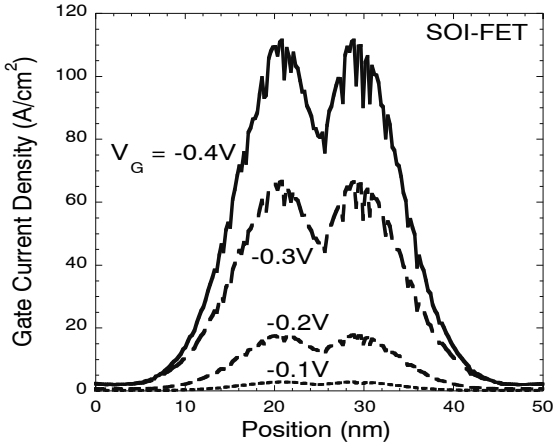

Fig. 6. Gate current density in the n-channel SOI FET with V_{SD} = 0V.and V_G a parameter.