Solid-State Electronics 200 (2023) 108553

Contents lists available at ScienceDirect

Solid State Electronics

journal homepage: www.elsevier.com/locate/sse

Non-local transport effects in semiconductors under low-field conditions

M.G. Ancona [a,b,*], S.J. Cooke [b]

[a] Department of Electrical and Computer Engineering, Florida State University, Tallahassee, FL 32310, USA
[b] Electronics Science and Technology Division, Naval Research Laboratory, Washington, DC 20375, USA

ARTICLE INFO

Handling Editor Francisco Gamiz

Keywords:
Electron transport
Non-local effects
Continuum modeling
Channel transport

ABSTRACT

Macroscopically non-local effects arise in semiconductor devices whenever the mean free path and/or the deBroglie wavelength are not small compared to geometry/flow length scales. In such cases standard diffusion-drift (DD) theory becomes inaccurate and in need of revision, with the best known example being density-gradient (DG) theory. Here we consider a similarly motivated gradient correction to the electron-lattice interaction that accounts for non-locality in the transport physics. Versions of DD and DG theory with this correction are discussed and the DD-based approach is illustrated by applying it to the analysis of long-channel field-effect transistors where it provides a new physics-based approach for treating surface scattering.

1. Introduction

Macroscopically non-local effects are common in electron transport in semiconductor devices, occurring whenever the mean free path (mfp) and/or the deBroglie wavelength are not small compared to geometry/flow length scales. When such effects are important, standard diffusion-drift (DD) theory becomes inaccurate and should be modified to account for the non-local effects. One well-known example is provided by density-gradient (DG) theory [1], and here we investigate another in which the non-locality is instead manifested in the transport physics.

The importance of non-local transport effects associated with the mfp is gauged by the Knudsen number defined as the ratio of the mfp to a characteristic length scale of the situation. When this number is appreciable, one is in the Knudsen regime and governing macroscopic equations will contain various gradient-dependent correction terms. The classic derivation of this physics is from the Boltzmann equation via the Chapman-Enskog expansion [2,3]. An analogous thing happens in a quantum mechanical context with DG theory wherein the equation of state for the electron gas contains an added gradient term that provides a lowest-order accounting for quantum non-locality [1]. Here, using methods of classical field theory [4], we undertake a similar development but with the gradient corrections now capturing classical and/or quantum non-locality effects on scattering.

In semiconductor devices non-local transport effects are most impactful in high-field and quasi-ballistic situations, however, we leave these cases for the future and instead focus here on the much simpler problem of a long-channel field-effect transistor (FET) under low-field conditions. The conventional modeling approach of this situation uses DD or DG theory, but this is questionable given that the electron mfp (and perhaps the deBroglie wavelength) is not small compared to the inversion layer thickness. The kinds of physical effects we are concerned with may be understood by considering three hypothetical boundary layer flows depicted in Fig. 1, each dominated by a different scattering mechanism. Fig. 1a corresponds to the situation of ordinary Navier-Stokes fluid mechanics with the effect of the boundary transmitted into the flow by inter-particle scattering (expressed macroscopically as a viscous stress) and resulting in the non-uniform average velocity profile shown. Because electron–electron scattering is generally weak, this picture is almost always irrelevant to electron transport [5]. Fig. 1b instead pictures a flow of electrons inside a semiconductor in which it is assumed that there is no electron–electron scattering, that the deBroglie wavelength is short enough that quantum non-locality plays no role, and that the wall scattering is diffuse. The mfp is assumed to be long so that the effect of the diffuse wall scattering extends non-locally out into the flow, again producing a non-uniform average velocity profile as shown. Lastly, in Fig. 1c a second electron flow is considered in which all is the same as in Fig. 1b except that the mfp is now assumed short and the deBroglie wavelength is instead taken to be long as depicted by the smearing of the green color associated with each electron that corresponds to the probability of it being at any given location. Within this Born interpretation the diffuse scattering by the boundary will be non-local with a probability proportional to the overlap of a given electron's 'spread' with the boundary potential. In this way, quantum non-locality can also produce a non-uniform average velocity profile as

* Corresponding author at: Department of Electrical and Computer Engineering, Florida State University, Tallahassee, FL 32310, USA.
E-mail address: mancona@fsu.edu (M.G. Ancona).

https://doi.org/10.1016/j.sse.2022.108553

Available online 1 December 2022

shown in the figure.

2. Theory

As in previous work [1], we here employ classical field theory methods [4] to formulate our generalized electron transport description. Such a development entails: (a) postulating the particular continua and field variables that form the theory; (b) constraining the variables to satisfy classical laws of physics such as those of conservation, electromagnetism, and thermodynamics; and (c) proposing appropriate material response functions to quantify the reactions of the defined continua to imposed forces. The most important equation that results from steps (a) and (b) is the expression of linear momentum balance in the electron gas that takes the form:

$$m_n \frac{d^n \boldsymbol{u}}{dt} = -q\nabla\varphi^{nDG} + q\boldsymbol{E}^n \tag{1}$$

$$\text{where } \Phi^{nDG} \equiv \psi - \varphi^{nDG} \tag{2}$$

$$\varphi^{nDG} = \varphi^n - \frac{2}{s}\nabla(b_n \nabla s) \qquad s \equiv \sqrt{n}$$

defines the DG electrochemical potential [1]. In these equations m_n is the electron mass, n is the electron density, $\boldsymbol{u}$ is the electron gas velocity, $\boldsymbol{E}^n$ is the force (per charge) exerted by the lattice on the electron gas, Ψ is the electric potential, φ^n is the DD chemical potential, and b_n is the DG coefficient. For most situations the inertia term on the left side of (1) is negligible in which case the theory simplifies considerably.

For the present paper the crucial material response function is an expression for $\boldsymbol{E}^n$. In DD theory, this electron-lattice interaction force is treated as local and instantaneous, being proportional to the average electron velocity and with the proportionality constant being the inverse mobility. To account for non-local scattering effects of either classical (Fig. 1b) or quantum (Fig. 1c) origin we here add in a velocity gradient correction. For reasons of rotational invariance we assume a Laplacian so that the material response function describing the electron-lattice interaction force is:

$$n\boldsymbol{E}^n(\boldsymbol{u}) = -\frac{n\boldsymbol{u}}{\mu_n} + \gamma_n n\nabla^2\boldsymbol{u} = -\frac{n\boldsymbol{u}}{\mu_n} + \gamma_n n[\nabla(\nabla \bullet \boldsymbol{u}) - \nabla \times \omega] \tag{3}$$

$$\text{where } \omega \equiv \nabla \times \boldsymbol{u}$$

where $\boldsymbol{\omega}$ is the vorticity, γ_n is a material parameter gauging the strength of the gradient effect in the gas, and the second equality follows from a vector calculus identity. Inserting this function into (1) results in a corrected DD or DG theory which we correspondingly refer to as either velocity-gradient (VG) or generalized-gradient (GG) theory.

3. FET analysis

We begin with a scaling analysis in order to clarify the flow regime encountered in a typical FET. To this end, it is readily shown that the relevant length scales of the FET problem are the gate length L, the depletion layer width L_D^{depl}, the inversion layer thickness L_D^{inv}, the DG length scale $\lambda_{DG} \equiv \sqrt{qb_n/k_BT}$ and the VG length scale $\lambda_{VG} \equiv \sqrt{\mu_n\gamma_n}$. Comparing the relative sizes we conclude the following: (i) Because L_D^{depl} is not small compared to L, the full 2D electrostatics should be solved; (ii) because λ_{VG} is often larger than L_D^{inv}, DD/DG theory is typically inappropriate and the velocity-gradient correction in (3) should be included; and (iii) because λ_{DG} is typically much less than L_D^{inv} and λ_{VG}, for most purposes one can use VG rather than GG theory to analyze the FET problem.

On the basis of the foregoing analysis we now apply VG theory to a long-channel Si FET under low-field conditions. We assume diffuse scattering at the Si-SiO_2 interface and that there is no vorticity injection from the contacts. Solution profiles obtained from the VG simulation with $V_{DS} = 1V$ are plotted showing the electron density (Fig. 2a), the horizontal velocity (Fig. 2b), and the vorticity generated by the interface scattering (Fig. 2c). Profiles of density and velocity along a cutline across the boundary layer are also shown in Fig. 3a. As expected, the VG effect clearly produces a velocity boundary layer associated with surface scattering much like those depicted in Fig. 1b and 1c.

The effect of this surface scattering on the device characteristics are presented in Fig. 3b where we compare IV curves for cases with full slip (specular scattering) and no slip (diffuse scattering). The reduction in current associated with Si-SiO_2 interface scattering is evident. Note that a conventional DD treatment is identical to the specular scattering case except that one substitutes a "channel mobility" for the bulk mobility which effectively scales down the specular-scattering result to match the diffuse-scattering IV curve. This is qualitatively and practically effective, but among other things it requires making adjustments to the channel mobility if the physics beyond the pinch-off point is to be captured properly.

4. Final comments

Although the DD analysis of FETs is very well established and practically useful, we argue that its treatment of surface scattering ignores the macroscopically non-local nature of this scattering and that a

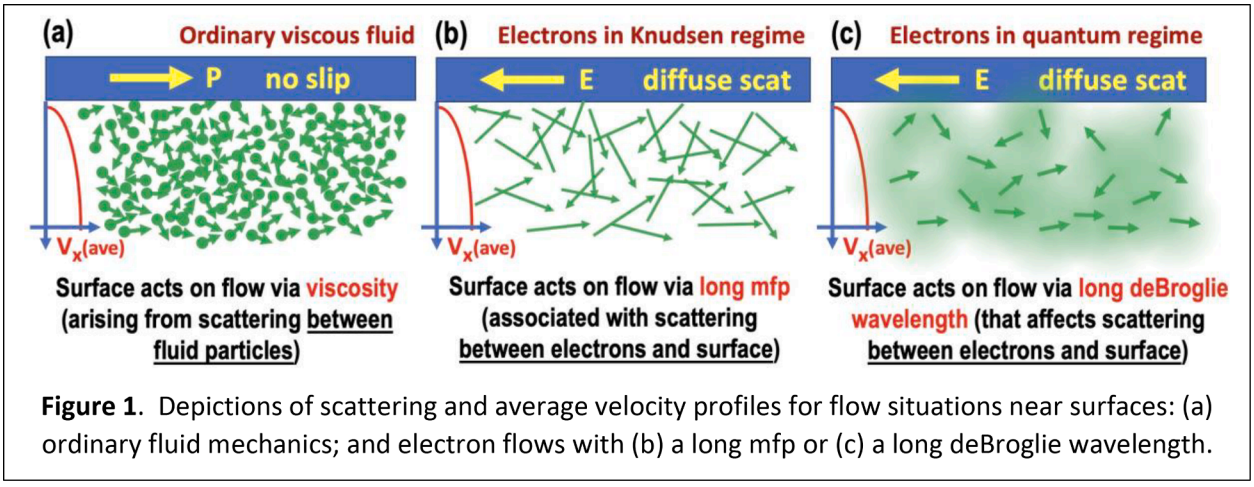

Figure 1. Depictions of scattering and average velocity profiles for flow situations near surfaces: (a) ordinary fluid mechanics; and electron flows with (b) a long mfp or (c) a long deBroglie wavelength.

Fig. 1. Depictions of scattering and average velocity profiles for flow situations near surfaces: (a) ordinary fluid mechanics; and electron flows with (b) a long mfp or (c) a long deBroglie wavelength.

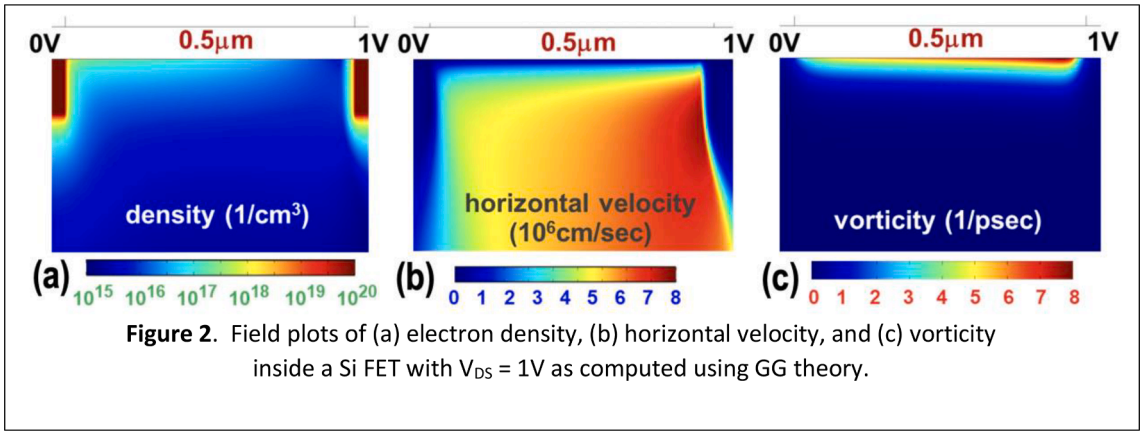

Figure 2. Field plots of (a) electron density, (b) horizontal velocity, and (c) vorticity inside a Si FET with V_{DS} = 1V as computed using GG theory.

Fig. 2. Field plots of (a) electron density, (b) horizontal velocity, and (c) vorticity inside a Si FET with $V_{DS} = 1$ V and $V_{GS} = 1$ V as computed using VG theory.

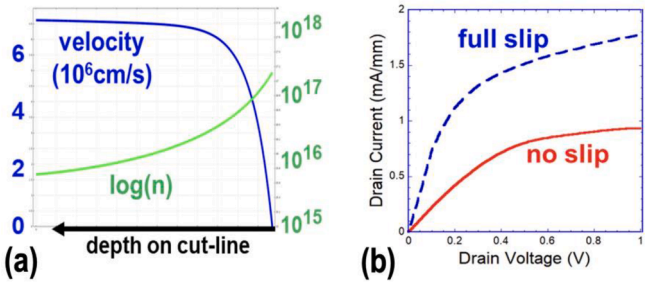

Figure 3. Plots of (a) cutlines across the channel in the FET of Fig. 2, and (b) the IV curves of the FET with V_{GS} = 1V as computed assuming full slip (specular scattering) or no slip (diffuse scattering).

Fig. 3. Plots of (a) cutlines across the channel in the FET of Fig. 2, and (b) the IV curves of the FET with $V_{GS} = 1$ V as computed assuming full slip (specular scattering) or no slip (diffuse scattering).

proper formulation should include a gradient correction in the material response function characterizing the electron-lattice interaction. Introducing such a correction leads to the governing PDEs having an additional solution variable, namely, the vorticity. Applied to analyzing an FET we find the expected qualitative behavior. It is not clear if this approach has practical value for analyzing FETs, but a similar correction is expected to also be important for high-field and nanodevice situations, and its inclusion will be studied in future.

Declaration of Competing Interest

Neither author has any conflicts of interest, either potential or actual, associated with this work.

Data availability

Data will be made available on request.

Acknowledgement

The authors thank the Office of Naval Research for funding support at the Naval Research Laboratory, and the first author thanks Prof. Petru Andrei of Florida State University for his comments and hospitality.

References

[1] Ancona MG. Density-gradient theory: A macroscopic approach to quantum confinement and tunneling in semiconductor devices. J Comput Electron 2011;10:62–97.
[2] Chapman S, Cowling TG. The mathematical theory of non-uniform gases. Cambridge, U.K.: Cambridge University Press; 1970.
[3] Burnett D. The distribution of molecular velocities and the mean motion in a non-uniform gas. Proc Lond Math Soc 1936;2:382–435.
[4] Truesdell CA, Toupin R. The classical field theories, Handbuch der Physik, **III/1**. Berlin: Springer-Verlag; 1960.
[5] Polini M, Geim AK. Viscous electron fluids. Phys Today 2020;73:28.