

Three-Dimensional Quantum Transport in Nanosheet FETs: Effects of Contacts, Geometry, and Multi-Stacks

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Abstract—In this work, we have performed large-scale three-dimensional quantum transport simulations of nanosheet FETs with multiple stacks. We have found that carrier transport involving complex current paths strongly depends on the device geometry and contact configuration. Phonon scattering can enhance carrier injection into nanosheet channels by mitigating carrier reflection and facilitating momentum transfer, in contrast to the conventional scattering-induced current degradation. Significant variation in transport among the stacked channels is observed in three-stacked devices, particularly in the top contact structure, reflecting the non-uniform carrier transport characteristics in stacked NSFETs.

Index Terms—Nanosheet Field Effect Transistors (NSFETs), Three-dimensional quantum transport, non-equilibrium Green's function (NEGF), phonon scattering, carrier reflection, device geometry, contact configuration

I. INTRODUCTION

Nanosheet FETs (NSFETs) have emerged as promising next-generation devices to overcome the electrostatic limitations of conventional FinFETs [1-3], owing to their superior electrostatic control and improved scalability enabled by the gate-all-around structure. However, as device dimensions continue to shrink, quantum mechanical effects become increasingly important in determining carrier transport characteristics. In particular, the abrupt transition from wide source/drain regions to a narrow channel induces strong quantum confinement and mode mismatch, along with complex current paths arising from the contact and device geometry, all of which play important roles in determining carrier transport characteristics [4–7]. Understanding how these quantum effects interact with scattering mechanisms is therefore essential for accurately describing transport in nanosheet FETs.

In this work, we use the non-equilibrium Green's function (NEGF) formalism to investigate how device geometry and contact configuration influence transport in NSFETs. By comparing phonon-dissipative and ballistic transport under identical electrostatic potential, we examine the structure-dependent role of phonon scattering and identify how scat-

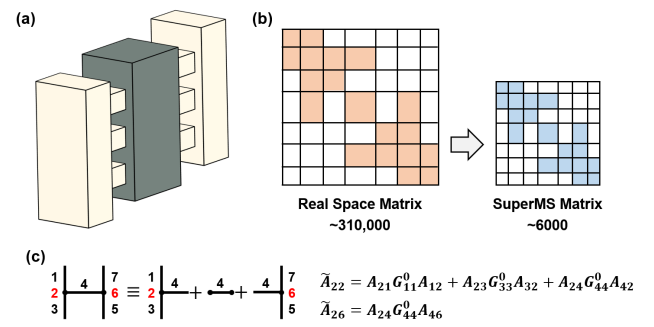


Fig. 1. Schematics of (a) three-stacked NSFET, (b) Hamiltonian size reduction using the SuperMS method, which reduces the size from 310,000 in real space to 6,000 in mode space for the three-stacked top contact device, and (c) Schur complement formulation for node 2 in the coupled-RGF framework.

tering modifies carrier injection and transport characteristics. The analysis is further extended to multi-stacked devices to explore transport behavior in more realistic NSFET architectures and to assess channel-to-channel transport variation in stacked structures.

II. SIMULATION METHODOLOGY

The NSFETs are simulated using an effective-mass Hamiltonian within the super cell mode space (SuperMS) framework [8-10]. To efficiently handle the computational complexity of realistic three-dimensional nanosheet devices, the entire device is partitioned into source/drain, bridge, and junction blocks, and the Hamiltonian of each block is individually reduced through the SuperMS approach. This block-wise size reduction greatly decreases the Hamiltonian dimension while preserving the essential real-space physics, enabling a reduction of a few orders of magnitude in what would otherwise be a prohibitively high cost of three-dimensional quantum simulation of complex geometries.

The coupled-RGF scheme [10] is employed to accurately capture multidirectional carrier transport in NSFETs,

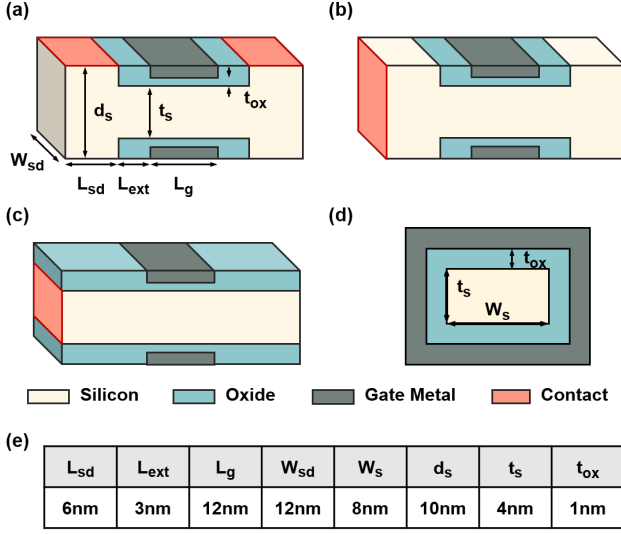


Fig. 2. Schematics of single-stacked NSFETs with (a) top contacts, (b) side contacts, and (c) device with uniform cross-section considered for comparison. (d) shows the cross-section view of the channel region. (e) Table of geometrical parameters, where W_s , d_s , and t_s represent the sheet width, sheet pitch and sheet thickness, respectively. The source and drain are doped to 10^{20} cm^{-3} , while the channel and extension regions are intrinsic, using an abrupt source/drain doping profile.

enabling efficient quantum transport calculations in three-dimensional structures with non-uniform current paths. Phonon scattering is incorporated within the self-consistent Born approximation to account for carrier scattering effects. For direct comparison, ballistic transport is calculated non-self-consistently using the same electrostatic potential obtained from the phonon scattering simulation, which allows a direct evaluation of the impact of phonon scattering on current transport.

By combining SuperMS Hamiltonian reduction with the coupled-RGF scheme, our simulation framework allows full three-dimensional quantum transport simulations to be carried out at a practical computational cost of approximately one hour per bias point. This makes simulations of realistically sized nanosheet devices both feasible and computationally efficient while maintaining highly accurate quantum mechanical transport analysis. The proposed framework is shown in Fig. 1.

III. RESULTS

A. Effect of Geometry and Contact Configuration

We have simulated NSFETs with top contacts and side contacts, as shown in Figs. 2 (a) and (b) for a one-stack NSFET. Note that currents are injected from wide source/drain regions into narrow channels in NSFETs, making them distinct from uniform cross-section device of Fig. 2 (c). In

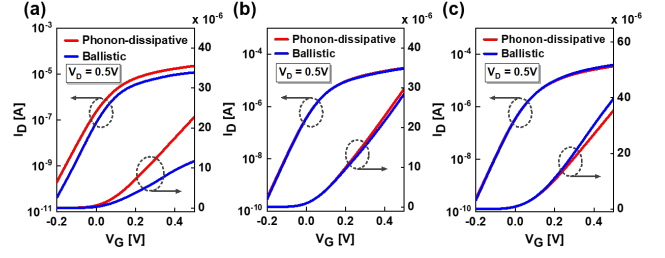


Fig. 3. Transfer characteristics for phonon-dissipative and ballistic transport in (a) top contact, (b) side contact, and (c) side uniform structures, shown in both linear and logarithmic scales at $V_D = 0.5V$.

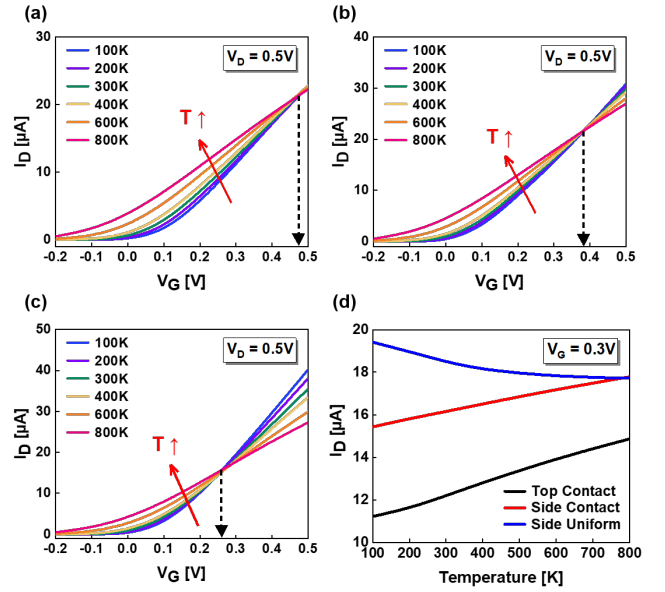


Fig. 4. Transfer characteristics at temperature ranging from 100K to 800K for (a) top contact, (b) side contact, and (c) side uniform structures at $V_D = 0.5V$. (d) shows the drain current as a function of temperature at $V_G = 0.3V$.

Figs. 3 (a)-(c), ballistic currents in NSFETs are significantly lower than in uniform devices due to reflections at the channel entrance. In top-contact configuration, the ballistic current is further reduced because a change in momentum is required for carriers to enter the channel.

Phonon scattering has traditionally been considered to cause current degradation. However, it is also known that scattering can facilitate carrier transport through carrier redistribution and mode coupling [11-14]. Our results support this interpretation, showing that phonon scattering can enhance current depending on the current path by mitigating carrier reflection at the constriction and facilitating momentum transfer [15]. The competition between these current-enhancing mechanisms and the conventional scattering-

induced degradation determines the overall impact of phonon scattering. In the uniform structure of Fig. 3(c), where no constriction-induced reflection exists, phonon scattering only introduces current degradation, resulting in a lower current than in the ballistic case. In contrast, in the NSFET structures shown in Figs. 3(a) and 3(b), phonon scattering reduces carrier reflection at the constriction, allowing more carriers to enter the channel and leading to a higher current than in the ballistic case [11,12]. This effect is observed in both top and side contact structures. Furthermore, in the top contact NSFET of Fig. 3(a), phonon scattering additionally assists momentum transfer for vertically injected carriers, resulting in a more pronounced current enhancement compared to the side contact structure.

This contrasting behavior is further supported by the temperature-dependent characteristics in Fig. 4. The zero-temperature coefficient (ZTC) point, defined as the bias at which the drain current becomes insensitive to temperature, exhibits a clear structural dependence. In the uniform device, the ZTC point appears at a lower bias because the conventional mobility degradation due to phonon scattering dominates the temperature dependence. In contrast, the ZTC point shifts to a higher bias in NSFETs, where the beneficial effect of phonon scattering in reducing carrier reflection competes with and partially compensates for the scattering-induced current degradation. As shown in Fig. 4(d), at $V_G = 0.3$ V, near the ZTC region where the trend between structures changes, the top contact structure exhibits a stronger temperature dependence than the side contact structure. This behavior indicates a larger contribution of phonon-assisted carrier transport in the top-contact configuration, where the beneficial role of phonon scattering is more pronounced.

B. Multi-Stack Effect

Three-stacked NSFETs are analyzed to examine the variation in transport among the stacked channels. The three-stack structure is derived from the single-stack device while maintaining the same geometrical parameters except for a reduced sheet pitch from 10nm to 8nm. Top and side contact configurations are simulated to investigate to examine the effect of contact configuration. Gaussian doping profiles are employed in the extension regions, where the peak concentration is positioned at the beginning of the extension regions with a standard deviation of 0.5nm.

Fig. 5 presents the phonon-dissipative and ballistic currents at ON-state along with the phonon-assisted current ratio (I_{ph}/I_{bal}) for the top, middle, and bottom stacks. In the top contact structure, the current contribution varies significantly from the top to bottom stacks, whereas the side contact structure remains nearly uniform across all channels, leading to an increased phonon-assisted current

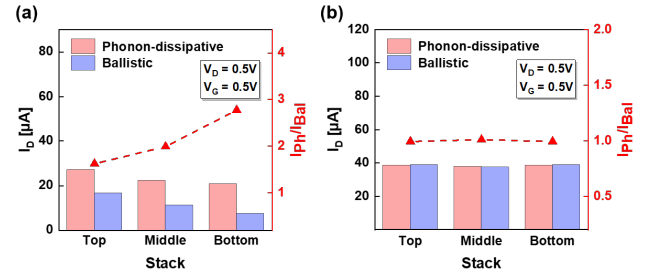


Fig. 5. Phonon-dissipative and ballistic currents with phonon-assisted current ratio (I_{ph}/I_{bal}) at $V_D=0.5$ V and $V_G=0.5$ V for (a) top and (b) side contact structures with 3 stacked channels corresponding to the top, middle, and bottom stacks.

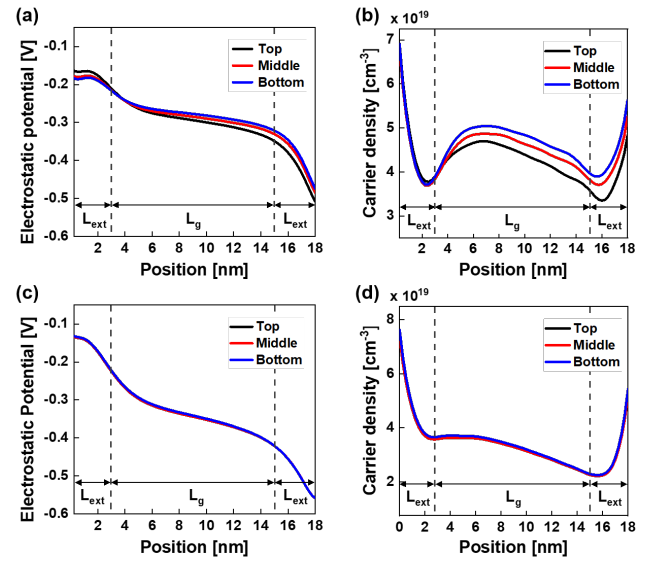


Fig. 6. (a) Electrostatic potential and (b) carrier density profiles along the channel and extension regions for the top, middle, and bottom stacks in the top-contact structure, and (c) and (d) those for the side-contact structure, respectively.

ratio. This behavior originates from contact-position-induced asymmetry with vertical injection causing non-uniform carrier distribution, while lateral injection maintains even transport across stacks. This interpretation is further supported by the electrostatic potential profiles and carrier densities shown in Figs. 6(a) and 6(b), which exhibit clear stack-to-stack variations in the top contact structure. In contrast, nearly identical potential and carrier density profiles are obtained in the side contact case, as shown in Figs. 6(c) and 6(d), indicating a much more balanced transport distribution among the three channels.

To examine the impact of the source/drain doping condition, the doping concentration was increased to $3 \times 10^{20} \text{ cm}^{-3}$. Figure 7 shows that the transport characteristics

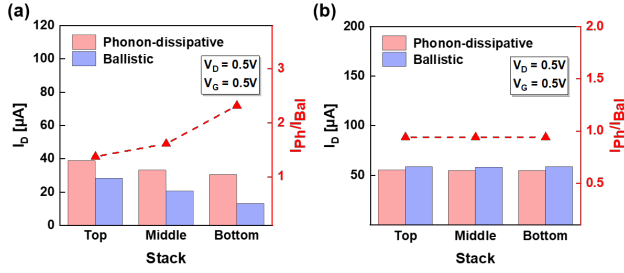


Fig. 7. Phonon-dissipative and ballistic currents with phonon-assisted current ratio (I_{ph}/I_{bal}) under a source/drain doping condition of $3 \times 10^{20} \text{ cm}^{-3}$ at $V_D=0.5\text{V}$ and $V_G=0.5\text{V}$ for (a) top and (b) side contact structures.

remain qualitatively similar under a higher doping condition. The enhanced carrier injection from the heavily doped source/drain regions increases both the phonon-dissipative and ballistic currents across all channels. In addition, the phonon-assisted current ratio is slightly reduced, indicating that the relative contribution of phonon-assisted transport becomes less significant as carrier injection improves. Nevertheless, the top contact structure continues to exhibit stack-dependent transport variation, whereas the side contact structure preserves a nearly uniform current distribution among the three channels.

IV. CONCLUSIONS

Our results show that phonon scattering in NSFETs should not be viewed simply as a conventional source of current degradation. Instead, its impact is dictated by the device geometry and contact configuration, leading to different transport characteristics depending on the device structure. Capturing this behavior requires large-scale three-dimensional quantum transport simulations, which provide a physics-based framework for the analysis and optimization of NSFETs, as demonstrated in this work.

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