Thin film three-dimensional topological insulator metal-oxide-semiconductor field-effect-transistors: A candidate for sub-10nm devices

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Thin film three-dimensional topological insulator metal-oxide-semiconductor field-effect-transistors: A candidate for sub-10 nm devices

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Three-dimensional (3D) topological insulators (TI) are a new state of quantum matter in which surface states reside in the bulk insulating energy bandgap and are protected by time-reversal symmetry. It is possible to create an energy bandgap as a consequence of the interaction between the conduction band and valence band surface states from the opposite surfaces of a TI thin film, and the width of the bandgap can be controlled by the thin film thickness. The formation of an energy bandgap raises the possibility of thin-film TI-based metal-oxide-semiconductor field-effect-transistors (MOSFETs). In this paper, we explore the performance of MOSFETs based on thin film 3D-TI structures by employing quantum ballistic transport simulations using the effective continuous Hamiltonian with fitting parameters extracted from *ab-initio* calculations. We demonstrate that thin film transistors based on a 3D-TI structure provide similar electrical characteristics compared to a Si-MOSFET for gate lengths down to 10 nm. Thus, such a device can be a potential candidate to replace Si-based MOSFETs in the sub-10 nm regime. © 2014 AIP Publishing LLC.

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I. INTRODUCTION

As the gate length of metal-oxide-semiconductor field-effect-transistors (MOSFETs) based on traditional silicon technology shrink down to sub-10 nm channel lengths, the performance of the devices is degraded substantially due to several phenomena, such as quantum mechanical tunnelling of carriers from source (S) to drain (D), drain induced barrier lowering (DIBL), diffusion of random dopant atoms from S/D into the channel, stochastic and random variations in device dimensions, high contact resistance, etc.^{1–4} Hence, exploring new materials that exhibit advantages with respect to any of these challenges is of great interest. Different alternative materials such as carbon nanotubes,⁵ graphene,⁶ III–V materials,⁷ etc., have been proposed as possible candidates to replace silicon technology in the sub-10 nm regime. Although each of these materials offers some advantages in comparison to Si, it is noted that the S/D contacts in all these devices need to be highly doped, which renders them extremely susceptible to random dopant variations for decanometer technology. Apart from these materials, a junctionless transistor concept has been introduced recently, which eliminates S/D junction doping variations by employing a uniform dopant concentration in the channel/contact regions and, therefore, rendering insignificant the diffusion of dopant atoms from the S/D into the channel region. However, junctionless transistors can still be vulnerable to doping variations and may suffer from high contact resistance.^{1,3,4,8,9}

Three-dimensional (3D) topological insulators (TI) are a new state of quantum matter, which exhibit an insulating energy bandgap in the bulk, and at the same time have zero-

bandgap surface states on the sample boundary.^{10,11} It has been recently demonstrated that by adjusting the quantum confinement (TI-film thickness) between the surfaces of the 3D-TI, it is possible to create an energy bandgap on the protected surfaces and, hence, the TI can operate as a semiconductor.^{10,12,13} The basic idea is that a TI with a surface induced energy gap can have different bandgaps along the carrier transport direction, where the channel region is a semiconductor with a particular bandgap whereas the S/D regions are metallic surfaces with zero bandgap energy.¹⁴ Such a device is theoretically superior to MOSFETs or other proposed materials, since the process of doping the contacts is eliminated and will no longer be an issue. Furthermore, the fabrication process of a 3D-TI based technology should result in higher yield in comparison to rival materials such as graphene and carbon nanotubes.^{15–19}

In this paper, we explore the possibility of incorporating a 3D-TI as a channel material in a MOSFET by using a two-dimensional (2D) quantum simulation, which involves the self-consistent solution of Poisson-Schrödinger equations, followed by the extraction of relevant electrical characteristics for a double-gate (DG) thin-film transistor based on a 3D-TI. The results are compared with a MOSFET based on conventional silicon technology. The quantum ballistic transport in 2D is evaluated by the well-established non-equilibrium Green's function (NEGF) formalism.

II. SIMULATION APPROACH

A. Crystal structure of a 3D topological insulator

Topological insulators in three dimensions with insulating energy bandgaps in the bulk have been recently studied theoretically and experimentally.¹¹ The surface states of a 3D topological insulator consist of an odd number of

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FIG. 1. Figure obtained from Ref. 15. (a) Crystal structure of Bi₂Se₃ with three primitive lattice vectors denoted as $t_{1,2,3}$. A quintuple layer with Se1–Bi1–Se2–Bi1'–Se1' is indicated by the red square. (b) Top view along the z -direction. The triangular lattice in one quintuple layer has three different positions, denoted as A, B, and C. (c), Side view of the quintuple layer structure. Along the z -direction, the stacking order of Se and Bi atoms determines the TI film thickness and resultant bandgap.

massless Dirac cones, with a single Dirac cone being the simplest case. Theoretical and experimental studies have shown that layered stoichiometric crystals such as Sb₂Te₃, Bi₂Se₃, and Bi₂Te₃ can form topological insulators.¹⁰ This group of 3D-TIs exhibit non-trivial energy gaps larger than the thermal energy at room temperature, which makes them ideal for semiconductor applications. Furthermore, the topological surface states for these crystals are extremely simple and are described by a single gapless Dirac cone at the Γ point in the surface Brillouin zone. The band structure of these materials has also been studied experimentally using the angle-resolved photoemission spectroscopy (ARPES) method, and theoretically using density functional theory (DFT) calculations in which an effective low-energy Hamiltonian has been proposed by fitting the parameters from DFT calculation.^{10–13}

Sb₂Te₃, Bi₂Se₃, and Bi₂Te₃ share the same rhombohedral crystal structure with five atoms in each unit cell. Taking Bi₂Se₃ as an example, its crystal structure is shown in Fig. 1, which has a layered structure with a triangular lattice within each layer. It has a trigonal axis (three-fold rotation symmetry), defined as the z axis, a binary axis (two-fold rotation symmetry), defined as the x axis, and a bisectrix axis (in the reflection plane), defined as the y axis. The material consists of five-atom layers arranged along the z -direction, known as quintuple layers. In this article, we use the continuous low-energy Hamiltonian to approximate the bandstructure of the 3D-TI; hence, the exact position of individual atoms is not of great importance.

In order to study carrier transport in a 3D-TI, we propose to start with the effective low-energy Hamiltonian model to describe the bulk states near the Γ point for bulk material. These states are mainly contributed by 4 hybridized states of Se and Bi p_z orbitals, and the Hamiltonian is given by^{10,13,20}

$$H(\mathbf{K}) = \varepsilon_0(\mathbf{K})I_{4 \times 4} + \begin{bmatrix} M(\mathbf{K}) & B_0k_z & 0 & A_0k_- \\ B_0k_z & -M(\mathbf{K}) & A_0k_- & 0 \\ 0 & A_0k_- & M(\mathbf{K}) & -B_0k_z \\ A_0k_- & 0 & -B_0k_z & -M(\mathbf{K}) \end{bmatrix}, \quad (1)$$

where

$$\begin{aligned} \mathbf{K} &= k_x^2 + k_y^2 + k_z^2, \\ \varepsilon_0(\mathbf{K}) &= C_0 + C_1k_z^2 + C_2(k_x^2 + k_y^2), \\ M(\mathbf{K}) &= M_0 + M_1k_z^2 + M(k_x^2 + k_y^2), \\ k_{\pm} &= k_x \pm ik_y, \end{aligned} \quad (2)$$

except for the identity term $\varepsilon_0(\mathbf{k})$, the Hamiltonian in Eq. (1) is simply the 3D Dirac model with uniaxial anisotropy along the z -direction and $\mathbf{k}$ -dependent mass terms. This model has time-reversal symmetry and inversion symmetry. The parameter values used in Eq. (1) can be identified by fitting the energy spectrum of the effective Hamiltonian with that of the *ab-initio* calculation, and the relevant parameter values for Sb₂Te₃, Bi₂Se₃, and Bi₂Te₃ are listed in Refs. 14–17.

B. Carrier transport in topological insulators

Having constructed the effective Hamiltonian we can now proceed to model carrier transport in a TI-FET by the NEGF approach in the ballistic limit and ignoring all scattering mechanisms. The TI-FET structure that we have considered in this study is shown in Figure 2, where carrier transport is in the x -direction, z is the confinement direction, which is perpendicular to the transport direction and with a thickness that is determined by the number of quintuple layers (film thickness), and finally, the y direction is the width of the TI-FET which has a finite length of L_y . In order

FIG. 2. Schematic representation of the double-gate MOSFET considered in this work. T_{ox} is the thickness of the HfO_2 gate dielectric. The semiconductor film thickness (T_{film}) is 1.2 nm for the TI-based device, and 2 nm for the silicon-based device. The width of the device in the transverse direction, L_y , is assumed to be large.

to numerically solve quantum transport in the TI-FET using the corresponding Hamiltonian in Eq. (1), we need to discretize the Hamiltonian in the x and z directions by replacing the scalars k_x , k_z with differential operators $k_x \rightarrow -i\partial/\partial x$, $k_z \rightarrow -i\partial/\partial z$ and $k_y \rightarrow k_y$ (i.e., keeping k_y constant). Using the finite difference method (FDM), the discrete first and second derivatives of the wavefunction can be written as

$$\frac{\partial \psi}{\partial x} = \frac{\partial \psi_{i+1,j} - \partial \psi_{i-1,j}}{2\Delta x}, \quad (3)$$

$$\frac{\partial^2 \psi}{\partial x^2} = \frac{\partial \psi_{i-1,j} - 2\partial \psi_{i,j} + \partial \psi_{i+1,j}}{\Delta x^2}, \quad (4)$$

where i and j are the Cartesian mesh indices in the x , z direction, respectively. Correspondingly, the discretized

Hamiltonian of Eq. (1) can be divided into 5 matrices, as follows:²¹

$$H\left(\frac{\partial}{\partial x}, \frac{\partial}{\partial z}, k_y\right) = H_0(k_y) + H_x(k_y) + H_{xx}(k_y) + H_z(k_y) + H_{zz}(k_y), \quad (5)$$

and,

$$H_{xx}(k_y) = \begin{bmatrix} C_2 + M_2 & 0 & 0 & 0 \\ 0 & C_2 - M_2 & 0 & 0 \\ 0 & 0 & C_2 + M_2 & 0 \\ 0 & 0 & 0 & C_2 - M_2 \end{bmatrix}, \quad (6)$$

$$H_{zz}(k_y) = \begin{bmatrix} C_1 + M_1 & 0 & 0 & 0 \\ 0 & C_1 - M_1 & 0 & 0 \\ 0 & 0 & C_1 + M_1 & 0 \\ 0 & 0 & 0 & C_1 - M_1 \end{bmatrix}, \quad (7)$$

$$H_x(k_y) = \begin{bmatrix} 0 & 0 & 0 & -iA_0 \\ 0 & 0 & -iA_0 & 0 \\ 0 & -iA_0 & 0 & 0 \\ -iA_0 & 0 & 0 & 0 \end{bmatrix}, \quad (8)$$

$$H_z(k_y) = \begin{bmatrix} 0 & -iB_0 & 0 & 0 \\ -iB_0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -iB_0 \\ 0 & 0 & -iB_0 & 0 \end{bmatrix}, \quad (9)$$

$$H_0(k_y) = C_0 I_{4 \times 4} + \begin{bmatrix} (C_2 + M_2)k_y^2 + M_0 & 0 & 0 & -iA_0 k_y \\ 0 & (C_2 - M_2)k_y^2 - M_0 & -iA_0 k_y & 0 \\ 0 & iA_0 k_y & (C_2 + M_2)k_y^2 + M_0 & 0 \\ iA_0 k_y & 0 & 0 & (C_2 - M_2)k_y^2 - M_0 \end{bmatrix}, \quad (10)$$

where $I_4 \times 4$ is the identity matrix of rank four, and H_0 , H_x , H_z , H_{xx} , and H_{zz} , are the zeroth, first, and second derivatives of the Hamiltonian in Eq. (1) with respect to x and z . The final discretized Hamiltonian of Eq. (1) has the form²¹

$$H_{2D}(k_y) = \begin{bmatrix} H_R(1) & W_R & & & \\ W_R^+ & H_R(2) & W_R & & \\ & W_R^+ & H_R(3) & & \\ & & & \ddots & W_R \\ & & & W_R^+ & H_R(N_x) \end{bmatrix}, \quad (11)$$

where

$$H_R(i) = H_{0R} + V_R(i), \quad (12)$$

where H_{0R} is the discretized kinetic Hamiltonian of Eq. (2) and $V_R(i)$ is the diagonal matrix with elements that correspond to the potential $E_C - q\phi(x_i, z)$ in the i -th layer along the transport direction, where E_C is the conduction band edge, $q\phi(x_i, z)$ is the vacuum level potential, and q is the elementary charge. H_{2D} is a block tri-diagonal matrix of size $(N_z \times N_x) \times (N_z \times N_x)$ and block size of $N_z \times N_z$, where N_x , N_z are the number of mesh point in the x , z direction. The Hamiltonian in Eq. (1) is dependent on the transverse wavevector k_y and it is assumed that the transistor has a finite length L_y , that takes the values $k_y(n) = 2n\pi/L_y$ with n an integer.

Having built the real-space discretized matrix, the band-structure ($E - k$ relation) of the TI-FET for layer i repeating along the transport direction x can be obtained by solving the following eigenvalue problem:

FIG. 3. Bandstructure of Sb_2Te_3 for different film thicknesses and assuming that y -direction is infinite. It is evident that by adjusting the film thickness, semi-conducting or metallic behavior can be achieved in the topological insulator material.

$$(H_R(i) + W_R e^{+ik_x} + W_R^+ e^{-ik_x}) \psi_i = E_i \psi_i, \quad (13)$$

where k_x is the wavenumber in the transport direction, and E_i and ψ_i are the eigenvalue and eigenfunction of layer i , respectively. Figure 3 shows the bandstructure of a Sb_2Te_3 -based TI-FET for different values of T_{film} with $k_y = 0$. Various TI film thickness values have been used: 1.5, 3.5, and 9 nm, which correspond to 2, 5, and 10 quintuple layers, assuming that each quintuple layer has a thickness of 0.7 nm. It is evident that for TI film thickness up to 4 nm the surface states exhibit a finite energy bandgap due to strong quantum confinement in the z -direction, whereas increasing the TI film thickness above 5 nm will create topologically protected metallic surfaces. The existence of a finite bandgap for the TI-device, which is imposed by quantum confinement, implies that the 3D-TI is a semiconductor that can be used as a channel material for field-effect-transistors. Furthermore, the existence of a zero-bandgap state implies that the same TI-material can be used as a metallic source/drain contact without requiring any doping, thus eliminating the diffusion of random dopant atoms from source/drain into the channel region and all of the statistical variations associated with the doping process.

By combining these two effects, we introduce a new type of transistor: the confinement modulated bandgap transistor, which is a possible candidate for future sub-10 nm MOSFET technology. In this current study, we have assumed that the thicknesses of S/D and channel are all equal along the length of the device. Future studies will also consider a 3D-TI MOSFET with metallic contacts.

Figure 4 shows the calculated bandgap energy as a function of film thickness for Sb_2Te_3 , Bi_2Se_3 , and Bi_2Te_3 assuming $k_y = 0$. We can see that the bandgap energy decreases with increasing TI film thickness, and exhibits an oscillatory behaviour, which is a result of the strong interaction between the top and bottom surfaces in the 3D-TI structure. This oscillatory behaviour has already been reported using numerical and analytical solutions of the low-energy effective Hamiltonian.^{12,13}

C. Quantum transport modelling

The well-established NEGF formalism for layered structures has been used self-consistently with Poisson's equation in order to solve the quantum ballistic transport equations

and calculate the relevant physical parameters. The corresponding three-dimensional carrier density in the x - z plane can be written as²¹

$$n_{3D}(x, z) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} n_{2D}(x, z; k_y) dk_y, \quad (14)$$

where n_{2D} is the 2D carrier sheet density in the x - z plane and is obtained from

$$n_{2D}(x, z; k_y) = \int_{-\infty}^{+\infty} (f_s G_s \Gamma_s G_s^+ + f_d G_d \Gamma_d G_d^+) dE, \quad (15)$$

where $f_{s(d)}$ is the Fermi function at the source (s) and drain (d), respectively, and $\Gamma_{s(d)}$ is the broadening function defined by

$$\Gamma_{s(d)} = i(\Sigma_{s(d)} - \Sigma_{s(d)}^+), \quad (16)$$

where $\Sigma_{s(d)}$ is the self-energy matrix at the S/D, which can be evaluated by employing iterative methods such as the Sancho-Robio algorithm, or through exact solution of the boundary matrix eigenvalue problem.⁶ From the solution of the NEGF equations, the calculated electron density then

FIG. 4. Bandgap energy as a function of TI-film thickness, with $k_y = 0$. Oscillatory behaviour is a result of strong interaction between top and bottom surfaces in the TI structure.

serves as an input into a self-consistent two-dimensional Poisson solver to update the potential profile as follows:

$$\nabla^2 \phi^k(x, z) = -\frac{q}{\epsilon} \left(N_D + n_{3D}^k(x, z) e^{-(\phi^k - \phi^{k-1})/k_B T} \right), \quad (17)$$

where N_D is the donor atom concentration, and ϕ^k and n^k are the k -th self-consistent step solutions for potential and electron density, respectively. The 2D Poisson's equation was solved using COMSOL[®] multiphysics employing a finite element method in which the oxide material was assumed to be HfO_2 with a relative permittivity of 25. In this paper, we have chosen Sb_2Te_3 with a relative permittivity of 50 as the TI-FET channel material. The reason for this choice is that the relative permittivity of Bi_2Se_3 and Bi_2Te_3 are approximately 100, whereas that of Sb_2Te_3 is 50, and hence closer to the value of 12 for silicon. The influence of different channel materials on the performance of TI-FETs will be the subject of future studies.

The energy integration in Eq. (2) was computed using an adaptive integration method. The integration over transversal wavevector k_y and carrier injection energy E , in Eqs. (14) and (15) can be limited by looking at the physics of the problem at hand. The electron density in the x - z plane can be determined by performing the integrals in Eq. (14) in a limited energy range defined with respect to the local charge neutrality energy, E_N .⁵ In a semiconducting TI, due to the symmetry of the conduction and valence bands, E_N is expected to be at the midgap energy. Since the electrons are injected from the source/drain contacts into the device with a Fermi distribution of energies, the carrier density will exponentially tend toward zero for energies greater than $10k_B T$ from the top of conduction band. Hence, the energy range of the integral in Eq. (14) will be limited between E_N and $E_{C,max} + 10k_B T$. A similar argument can be made for integration over k_y . For wavevectors with corresponding energy greater than $10 \times k_B T$ the value of n_{2D} in Eq. (15) will exponentially decrease. Figure 5 shows the electron sheet density

FIG. 5. Two-dimensional electron density (n_{2D}) along transport direction (x) for a 10-nm channel length FET and for different values of transverse wavevector k_y at $V_{DS} = 0.4$ V and $V_{GS} = 0$ V. For k_y with corresponding energy values greater than 25 mV, 2D electron density decreases exponentially with k_y ; therefore, the integration range in Eq. (14) can be limited to $k_y = 0$ to 0.6 nm^{-1} , which reduces the computation time significantly.

n_{2D} along the carrier transport direction (x -direction) for different values of k_y .

III. RESULTS AND DISCUSSION

Figure 2 shows a schematic representation of the TI-FET considered in this study with a HfO_2 thickness of $T_{ox} = 1$ nm, and source/drain extensions of $L_S = L_D = 20$ nm. T_{film} is the thickness of the transistor body and equals 1.2 nm for the TI-FET and 2 nm for the silicon-based FET. We have assumed a finite width of 100 nm for the transverse dimension L_y ; however, this parameter does not have any significant influence on the simulation results as long as it is large in comparison to the gate length of the device, L_G . The S/D contacts have a doping density of 10^{21} cm^{-3} , while the channel region under the gate contact is considered to be undoped. In order to benchmark the performance of the TI-FET, two key transistor performance parameters, the subthreshold slope (SS) and $DIBL$, have been used, and are defined as follows:

$$SS = \frac{dV_{GS}}{d(\log_{10} I_{DS})}, \quad (18)$$

$$DIBL = \frac{(V_{th}|_{V_{DS}=0.05 \text{ V}} - V_{th}|_{V_{DS}=0.4 \text{ V}})}{(0.4 - 0.05)}, \quad (19)$$

where SS is determined in the subthreshold conduction region, and V_{th} and I_{DS} are the threshold voltage and drain current, respectively. The threshold voltage is defined as the gate voltage at which the second derivative of the drain current as a function of gate voltage reaches a maximum: that is, the value of gate voltage for which the derivative of transconductance (g_m) reaches a maximum²²

$$V_{th} = \frac{\partial g_m}{\partial V_{GS}} = \frac{\partial^2 I_{DS}}{\partial V_{GS}^2} \bigg|_{V_{DS}}, \quad (20)$$

where V_{DS} is fixed at a given bias and I_{DS} is the S/D current. Figure 6 shows the procedure of extracting V_{th} from the

FIG. 6. Procedure for obtaining V_{th} by computing the derivative of the transconductance. V_{th} has been calculated at $V_{DS} = 50$ mV and $V_{DS} = 400$ mV for a device with a 5 nm gate length. The difference in V_{th} is 60 mV.

FIG. 7. Figures of merit SS , $DIBL$, and V_{th} variations for TI-based FETs and Si-based FETs as a function of gate length, L_G . It is noted that in the quantum ballistic limit, neglecting all scattering mechanism, the 3D TI-based FETs has similar performance to that of a Si-based FETs for long channel devices ($L_G > 10$ nm).

derivative of the g_m with respect to V_{GS} . In this paper, TI devices with $L_G = 5$ nm have been considered at two different values of applied bias; $V_{DS} = 50$ mV and $V_{DS} = 400$ mV.

Figure 7 shows the variations of ΔV_{th} , SS and $DIBL$ as a function of gate length for TI and Si-based FETs in the quantum ballistic limit and ignoring all scattering mechanisms. In Figure 7(a), the variation of threshold voltage at $V_{DS} = 50$ mV, which is defined as $\Delta V_{th} = V_{th}(L_G) - V_{th}(L_G = 50 \text{ nm})$, is the difference between the V_{th} at a particular gate length L_G with respect to V_{th} at $L_G = 50$ nm. It is evident that as the gate length is reduced to 10 nm there is no difference in V_{th} variations, which corresponds to an absence of short channel effects and quantum mechanical tunnelling from source to drain. For gate lengths less than 10 nm both devices exhibit similar SS , $DIBL$, and ΔV_{th} behaviour, and as the gate length is reduced below 10 nm the performance of both device begins to deviate from the long channel values due to quantum mechanical tunnelling of carriers from source to drain and degradation of the gate-controlled electric field in the channel region, which results in a variation of threshold voltage. It can be observed that the TI-based FETs begin to deviate from long channel characteristics earlier than the Si-based FETs due to the high relative dielectric constant of 50 in comparison to that of Si, which is 12, and hence results in weaker gate control of the electric field over channel. However, it is worth to note that the threshold voltage variation of any Si-based FETs will, in reality, be several hundred millivolts greater than those reported here due to random dopant variations, which have been neglected in this study. Hence, the performance of Si-based FETs in terms of V_{th} variations will be significantly inferior than those reported here. Figure 7(b) shows the $DIBL$ versus gate length, which follows a similar trend similar in ΔV_{th} . The value of $DIBL$ at $L_G = 50$ is 140 and 120 mV/V for TI and Si-based FETs, respectively. The difference of 20 mV in $DIBL$ for long channel devices is due to the difference in dielectric constant between the two materials. In Figure 7(c) we can see that both TI and Si-based FETs start to deviate from the ideal 60 mV/dec subthreshold slope for gate length less than $L_G = 8$ nm.

Figure 8 shows the I_{DS} - V_{GS} curves of the DG-MOSFETs for $L_G = 5$ nm to 50 nm, and for both TI and Si-based devices. We can see that TI-based FETs have larger off-current in comparison to Si, which is due to the higher dielectric constant of TI material as explained previously.

Figure 9 shows the I_{DS} - V_{DS} curves for TI-based FETs with a gate length of 5 nm and 10 nm. For both devices, the transistors have a well-defined saturation region. However, the device with $L_G = 5$ nm has a higher output conductance due to increased tunnelling between source and drain contacts.

Figure 10(a) shows the first subband energy of the TI-based FET for different values of V_{DS} ranging from 0.05 V

FIG. 8. I_{DS} - V_{GS} characteristics for TI and Si-based FETs as a function of gate length at $V_{DS} = 50$ mV. The TI-based FETs have a higher off-current in comparison to Si-based FETs due to a higher dielectric constant and therefore weaker gate control over the channel.

FIG. 9. I_{DS} - V_{DS} curves for TI-based FETs with $L_G = 5$ nm and $L_G = 10$ nm. For $L_G = 5$ nm, the device exhibits a higher output conductance due to increased tunnelling current from source to drain.

to 0.4 V at $V_{GS} = 0.4$ V and $L_G = 10$ nm. In this case, the top of the barrier (maximum energy of the 1st subband) does not vary with changing V_{DS} , which implies that *DIBL* is not present for $L_G = 10$ nm. Figure 10(b) shows the first subband energy of TI-based FETs for different values of gate length at $V_{DS} = 0.4$ V and $V_{GS} = 0.6$ V. It is noted that the maximum energy of the 1st subband decreases with decreasing gate length due to *DIBL*, which degrades the performance of TI-based FETs for short channel transistors. Nevertheless, 3D TI-based devices can operate as a FET with performance parameters that are comparable to Si-based devices in the long channel limit ($L_G > 10$ nm), whereas, TI-based FETs performance will be worse than Si-based FETs for short channel devices ($L_G < 10$ nm). Despite the weaker performance of TI-based FETs for short gate length devices, it is possible to reduce the V_{th} variations of TI-based FETs by following the device design proposed by Ansari, which will be investigated in the futures studies.¹⁴

Regarding the mobility and scattering mechanisms, TI devices should theoretically demonstrate zero scattering due to topological protection of the surfaces; however, signatures of elastic and inelastic electron-phonon scattering has been recently reported, which should be studied further in the future works.²³ Of particular note is the availability of metallic and semiconducting states in the same topological

FIG. 10. (a) 1st subband energy of TI-based FET for different values of V_{DS} between 0.05 V and 0.4 V at a fixed bias of $V_{GS} = 0.4$ V and with $L_G = 10$ nm (b) 1st subband energy of TI-based FET for gate lengths of 3, 4, 5, 6, 7, 8, 10, and 20 nm with a fixed bias of $V_{DS} = 0.4$ V and $V_{GS} = 0.6$ V. Note that, maximum energy of the 1st subband decreases with decreasing gate length due to *DIBL*, which degrades the performance of TI-based devices.

material, which can be controlled by the degree of confinement, thus TI-based FET can be potentially used to replace the doped contacts of Si-based devices with metallic contacts, which is of great relevance for removing random dopant fluctuations in future semiconductor technologies in the sub-10 nm regime.¹⁴

IV. CONCLUSION

3D-TI materials such as Bi_2Se_3 , Bi_2Te_3 and Sb_2Te_3 could be a candidate to replace Si-based FET technology as the gate length of FETs are scaled below 10 nm. These materials can have metallic surfaces, which are topologically protected in the bulk bandgap, while exhibiting a surface bandgap due to confinement effects. This unique capability makes them an ideal structure for future semiconductor devices. The metallic state of a 3D-TI is ideal for S/D contact formation which eliminates doping processes in the contact regions and, hence, all the physical and technological challenges associated with random doping variations. The results in this paper have shown that in the quantum ballistic limit and in the absence of any scattering mechanisms, 3D-TI-based FETs in a double-gate design demonstrate similar

electrical characteristics in comparison to Si-based technology for long channel devices ($L_G > 10$ nm) and worse performance for short channel devices ($L_G < 10$ nm).

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