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Improvement of carrier ballisticity in junctionless nanowire transistors

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In this work we show that junctionless nanowire transistor (JNT) exhibits lower degree of ballisticity in subthreshold and higher ballisticity above threshold compare to conventional inversion-mode transistors, according to quantum mechanical simulations. The lower degradation of the ballisticity above threshold region gives the JNT near-ballistic transport performance and hence a high current drive. On the other hand, lower ballisticity in subthreshold region helps reducing the off-current and improves the subthreshold slope. A three-dimensional quantum mechanical device simulator based on the nonequilibrium Green's function formalism in the uncoupled mode-space approach has been developed to extract the physical parameters of the devices. © *2011 American Institute of Physics*. [doi:10.1063/1.3559625]

Thin-film silicon-on-insulator and multigate nanowire transistor structures are considered as a strong contender for the upcoming generation of ultrascaled transistors with gate length in the decananometer regime. The recently proposed junctionless nanowire transistor (JNT) exhibits excellent electrostatic control of the gate over the channel region, which strongly reduces short-channel effects.[1–4] However, at the nanometer scale regime the gate length becomes comparable to the mean free path of the carriers and electron–phonon interaction mechanisms (acoustic and optical phonons) can considerably reduce the drain current and hence degrade device performance (i.e., the mobility, subthreshold slope (SS), and current drive can be affected).[5–7] Several articles discussing the influence of electron–phonon scattering in silicon nanowires, using either a semiclassical approach based on Boltzmann equation or a quantum mechanical approaches based on the Schrödinger equation, the density matrix, the Wigner function, or Green's function can be found in the literature[7–11] but no solution has been proposed to minimize the degradation of device characteristics caused by electron–phonon interactions. Here, we show that the JNT architecture improves device performance in the presence of electron–phonon scattering by suppressing the effect of electron–phonon interaction in above threshold and enhancing electron–phonon interaction in the subthreshold region. These effects yield a higher current drive and a lower off-current than inversion-mode (IM) devices.

In a JNT device doping concentration in the channel is equal to that in the source and drain regions. Unlike in IM and accumulation-mode devices the current flows in a neutral (undepleted) channel in the center of the device, and not in surface channels. Classical simulations and experiments show that these types of devices have excellent electrical characteristics such as low drain induced barrier lowering effect, excellent short-channel SS and low leakage currents at high temperature.[12–16] The output characteristics of both conventional (N^+-P-N^+) and junctionless ($N^+-N^+-N^+$) devices were simulated using a three-dimensional quantum simulator solver based on the well-established nonequilibrium Green function (NEGF) formalism in the mode-space approach. Electron–phonon interaction is handled by the self-consistent Born approximation method. In next section we briefly discuss the simulation method and device design.

A comprehensive description on the use of the NEGF formalism for quantum transport and of the self-consistent Born approximation for handling electron–phonon interactions can be found in the literature.[7,17–20] It is well established that electron–phonon interactions decrease the drain current (compared to the case ballistic transport) due to backscattering of injected carriers by the phonons. Among the different electron–phonon scattering mechanisms, the g-type optical phonon interaction is the dominant interaction as far as current reduction is concerned.[17,18] Hence, we only consider the g-type interaction here and use the same phonon energies and deformation potential parameters as in Ref. 18.

In this study, two n-channel devices with a gate-all-around structure and a rectangular cross section are used for comparison. The IM device has a p-type channel doping concentration of 10^{18} cm^{-3} and the JNT has an n-type doping concentration of 10^{19} cm^{-3}. Both devices have a gate length of 20 nm and 10-nm-long source drain extension. In order to compare the performance of JNT and IM devices in the presence of electron–phonon scattering we introduce the "degree of ballisticity," which is defined as ratio of current in the presence of scattering to the ballistic current. In order to make a reasonable comparison between the two type of devices, the output characteristic (i.e., I_{DS}-V_{GS} curve) has been shifted to obtain the same off-current of $I_{DS}=10^{-13}$ for both transistors.

Figure 1 shows the degree of ballisticity for silicon nanowire transistors with a cross section of 9×9 nm^2, 7×7 nm^2, or 5×5 nm^2. As one can see the degree of ballisticity in the JNT above threshold increases with the device cross section and is higher than in the IM device. The higher degree of ballisticity in the JNTs can be explained as follows. As the gate voltage V_{GS} is increased above threshold, the depletion region in the channel region decreases in size and the transistor behaves as a resistor with uniform doping and carrier concentration and, hence, with a smooth potential profile without any source/channel junction potential barrier. As a result, there is no reflection of carriers at the source-channel junction; all the carriers injected in the channel reach

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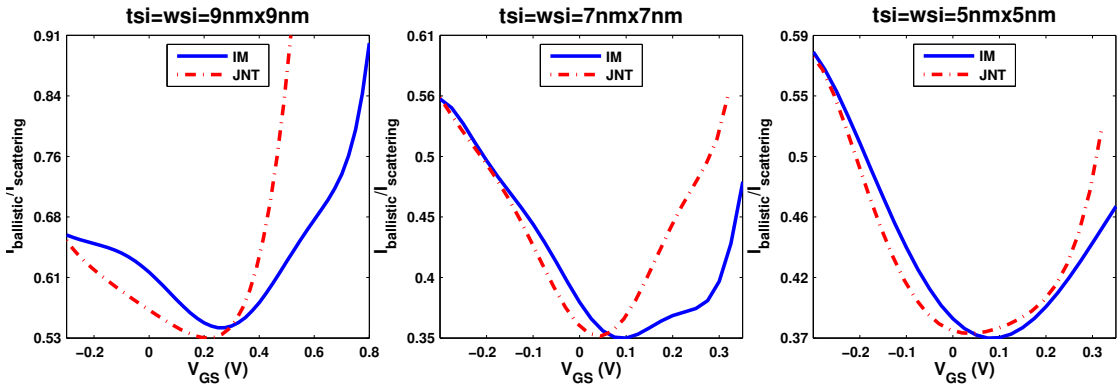


FIG. 1. (Color online) Degree of ballisticity in JNT and IM nanowire transistors with different cross section. The JNT has a higher (lower) degree of ballisticity than the IM device below (above) threshold.

to the drain side (except those backscattered by phonon scattering), resulting in high on-current and a high degree of ballisticity. This behavior is different from what happens in IM transistors where increasing V_{GS} above threshold creates an inversion charge and as, a result, a source/channel "junction" potential barrier. This potential barrier enhances the backscattering of injected carriers by optical phonons. Figure 2 shows the potential profile in a JNT and an IM transistor for $V_{GS}=V_{TH}+0.3$ V. As can be seen, there is no source/channel junction potential barrier in the JNT due to uniform doping of that structure.

Figure 1 also implies that in the presence of electron–phonon scattering the JNT has a lower degree of ballisticity than the IM transistor in the subthreshold region. This behavior results in a stronger reduction in the off current in the JNT than in the IM device, which in turn yields a higher, SS, in the JNT. In order to explain the difference in behavior between JNT and IM devices, the degree of ballisticity for IM nanowire transistors with the same doping concentration but with different cross sections has been plotted in Fig. 3. One can see that reducing the nanowire cross section decreases the degree of ballisticity. Figure 4 shows plots of the electron density profile in the middle of the channel (at a distance $x=L_g/2$ from the source) for both JNT and IM devices below threshold ($V_{GS}=V_{TH}-0.3$ V). One can see that in the junctionless device carriers are "squeezed" in the middle of the channel whereas in IM device carriers spread out through the whole cross section. In the subthreshold region, however, the JNT behave like an IM transistor with a small cross section and hence exhibits lower ballisticity.

The relationship between the enhancement of electron–phonon scattering and the reduction in effective nanowire cross-section has been extensively discussed by K. Uchida.[21] In this paper the authors have shown that the increase in electron–phonon scattering is the only mechanism responsible for degradation of the mobility in thin-body silicon MOSFETs, which corroborates our observation on improved performance of JNTs in the subthreshold region.

Three-dimensional quantum simulations are used to investigate the effect of electron–phonon interaction on the performance of JNTs and IM silicon nanowire transistors. In the presence of optical phonons, the JNT shows improved performance through reduced phonon scattering above threshold and increased phonon scattering below threshold, which gives JNTs a higher on/off current ratio than conventional IM transistors. This unique behavior arises from the "squeezing" of carriers in the center of the channel region in subthreshold operation and the absence of a source-channel potential barrier above threshold.

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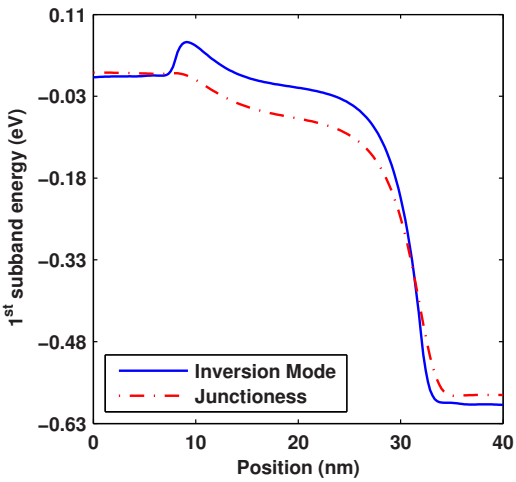


FIG. 2. (Color online) First subband profile for a JNT and an IM transistor at $V_G=V_{TH}+0.3$ V. Note the absence of a potential barrier at the source-channel "junction" in the JNT.

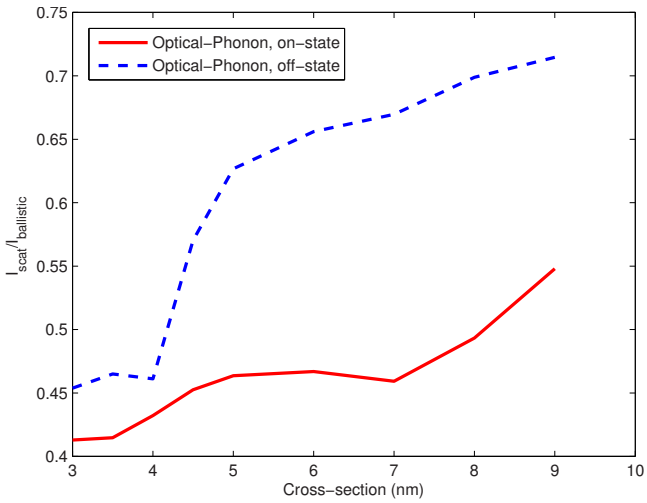


FIG. 3. (Color online) Degree of ballisticity in IM device as a function of silicon nanowire cross-section in the on-state and the off-state. Reducing the nanowire cross-section increases the effect of electron–phonon interaction leading to lower degree of ballisticity.

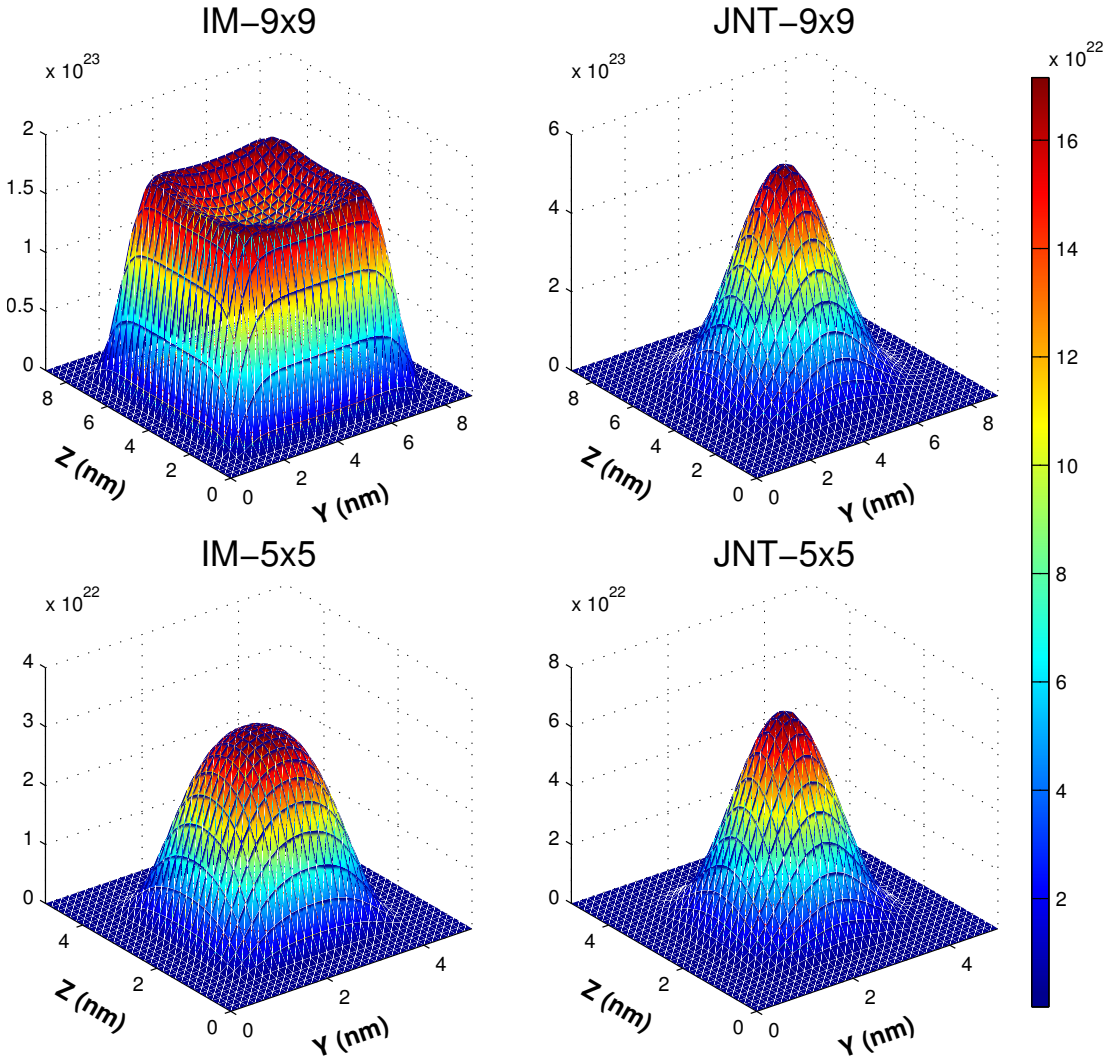


FIG. 4. (Color online) Electron density in the subthreshold regime ($V_G = V_{TH} - 0.3$ V) for JL and IM devices plotted at $x = L_g/2$. For $t_{si} = W_{si} = 5$ nm the "5 × 5" JNT and the "5 × 5" IM device have almost the same electron distribution profile. However, for $t_{si} = W_{si} = 9$ nm the carriers of the "9 × 9" JNT are more squeezed in the center of the channel region than in the 9 × 9 IM device which. As a result the JNT has a smaller effective cross section in subthreshold region than the IM device.

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