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Carrier Confinement in UTSOI Devices: Impact of Metal Gate Work Function

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Effect of Metal Gate Work Function on Quantum Confinement in UTSOI Devices

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***Abstract*—Carrier confinement in metal-gated UTSOI devices is examined as a function of gate work function using self-consistent quantum-mechanical simulations. The requirement to achieve a given off-current leads to a much weaker confining potential as the work function is shifted from the band edge. For both a conventional doped device and an undoped back-gated device, effective electric field and charge centroid position are studied versus gate work function. Implications of reduced confinement on device behavior, including short-channel effects, are discussed.**

***Index Terms*—Semiconductor device modeling, silicon on insulator technology, work function**

I. INTRODUCTION

REPLACEMENT of a polysilicon gate electrode with a metal one is expected to result in decreased inversion thickness of the gate insulator, improved sheet resistance of the gate, and reduced effects of statistical doping fluctuations and impurity scattering since work function shifts rather than channel dopants can be used to control the threshold voltage [1,2]. However, in addition to raising the threshold voltage, channel doping plays another important role for device operation: the electric potential generated by the space charge region of the dopants confines the carriers close to the surface, resulting in a strong gate-channel coupling. Thus, for a given off-current, an *n*-channel field-effect transistor (*n*FET) with an in-gap work function gate has less channel doping and thus has weaker confinement than an *n*FET with a band-edge work function gate. Using a drift-diffusion model, Ref. [3] discussed how a midgap gate leads to a buried carrier channel.

In the present work, the consequences of reduced confinement are investigated using the two-dimensional quantum-mechanical transport simulator QDAME [4] to accurately model the subthreshold electron distribution. Two UTSOI *n*FET devices are studied: an "undoped body" device having relatively thin buried oxide (BOX), with threshold voltage controlled by a back gate, and a "doped body" device having thick BOX, with threshold voltage determined by the uniform channel doping. A secondary objective of this work is to compare in detail the confining potentials generated by these two methods.

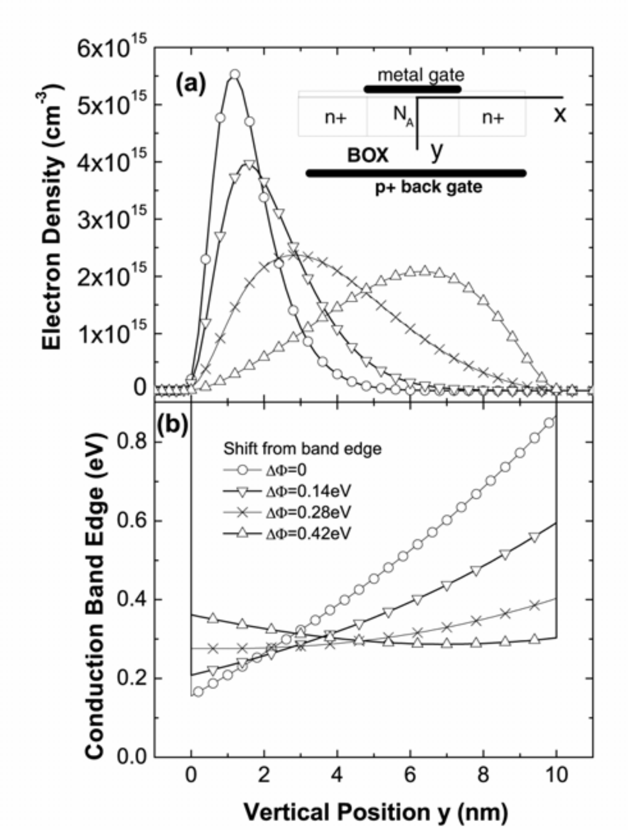

Fig. 1. (a) Electron density and (b) confining potential along a vertical cut in the SOI as function of position. Inset: Schematic of back gated UTSOI *n*FET with body doping N_A and *p*+ back gate at voltage V_{bg} used in this work.

II. PROBLEM SETUP AND SIMULATION RESULTS

We consider three shifts (ΔΦ) from the band-edge work function in "eighth gap" (0.14 eV) increments, so that the widely studied "fully silicided" gate [1,2] lies between the ΔΦ=0.28 eV ("quarter gap") and ΔΦ=0.42 eV cases. Because this paper focuses on studying the impact of the gate work function on the confining potential, we largely avoid two-dimensional effects by restricting ourselves to the low drain-source bias regime (V_{ds}=0.1 V). To compare the different gate work functions, we require each device to have the same off-current I_{off}=200 nA/µm at 100C, a value typical for a high-performance application. The basic device geometry is shown

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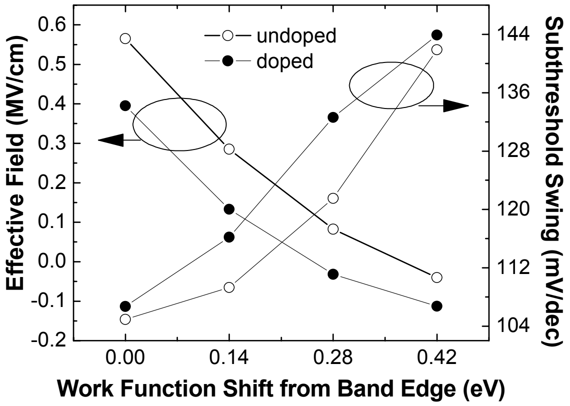


Fig. 2. Effective confining electric field and linear subthreshold swing at 100C as a function of work function shift from the band edge.

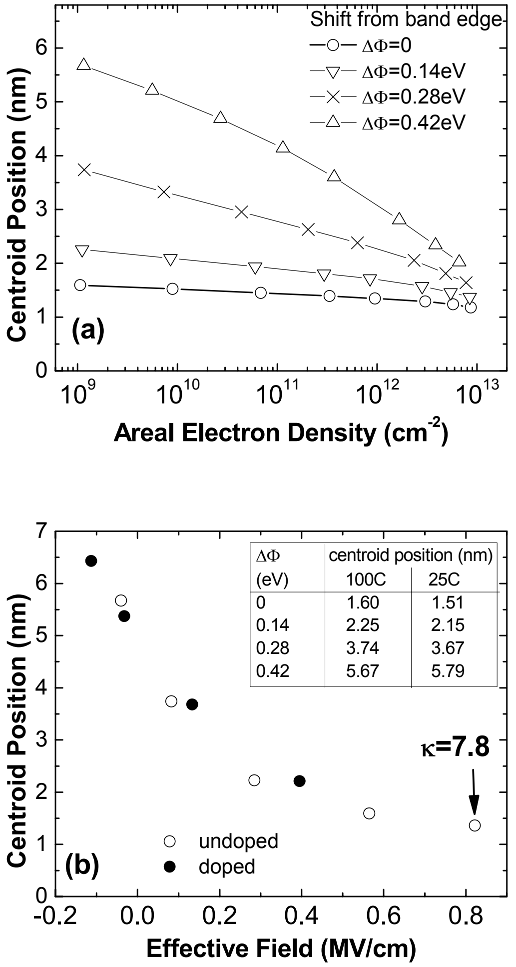
in the inset of Fig. 1. The undoped and doped body devices have BOX thicknesses 10 nm and 100 nm, respectively. Both devices have top oxide thickness 1 nm, SOI thickness 10 nm, and gate length 25 nm. Gate leakage is turned off, but wave function penetration into the oxide is included.

Fig. 1(a-b) illustrates the main result of this paper using the undoped body case. As the work function is shifted away from band edge, the back gate voltage V_{bg} must be made more positive (undoped body) or channel acceptor concentration N_A must be reduced (doped body) in order to achieve the I_{off} target. Thus, increasing $\Delta\Phi$ results in a dramatic degradation of the confining potential and movement of the quantum-mechanical electron distribution away from the interface.

To characterize this loss of confinement, Fig. 2 shows the effective vertical electric field, defined as the average of the local field weighted by the electron density, *n(y)*, $F_{eff} = \int F(y)n(y)dy / \int n(y)dy$, for the undoped and doped cases, evaluated at the channel center (x=0). The undoped case with $\Delta\Phi$=0.42 eV and the quarter-gap doped case have approximately zero effective confining field. As discussed in detail later, channel doping generates a weaker effective field than back gate bias with an undoped body.

A direct consequence of reduced gate-channel coupling is degraded subthreshold swing, as shown in Fig. 2, because the gate-channel capacitance is reduced significantly while the capacitances from the channel to other electrodes remain relatively unchanged. For the same reason, short-channel effects worsen markedly. For example, DIBL increases from 95 mV/V for $\Delta\Phi$=0 to 143 mV/V for $\Delta\Phi$=0.28 eV, in the undoped case.

Fig. 3(a) shows the position of the centroid of the electron distribution from the top interface as a function of areal electron density at the channel center (x=0) as the top gate voltage V_g is swept from off-state (V_g=0 V) to the on-state (V_g=1 V). Even in strong inversion, an in-gap work function has lower carrier density and a centroid farther from the interface. Also noteworthy is the significant difference in centroid position between the off-state and the inverted state, which increases as $\Delta\Phi$ increases, since the effective insulator thickness in strong inversion, rather than in the off-condition, is often used incorrectly as a scaling parameter.



ΔΦ (eV)	centroid position (nm) 100C	 25C
0	1.60	1.51
0.14	2.25	2.15
0.28	3.74	3.67
0.42	5.67	5.79

Fig. 3. (a) Centroid position from top interface as a function of areal electron density in the channel, spanning from the off-state (leftmost) to the on-state (rightmost). (b) Centroid position in off-state as a function of effective electric field at 100C.

Fig. 3(b) plots the centroid position as a function of F_{eff} for the undoped and doped cases and the four different work functions. A nearly universal correlation between effective confining field and centroid distance from the interface is observed. For zero effective field, the centroids are located nearly midway in the SOI body due to wave function repulsion from the two oxide barriers. As a limiting case of high gate-channel coupling, we also consider the effect of increasing the top oxide dielectric constant from κ=3.9 to κ=7.8, for $\Delta\Phi$=0. Despite the stronger confinement ($|V_{bg}|$ increases by 1.35 V), the centroid is still 1.35 nm from the top interface at 100C, corresponding to an effective oxide thickness of 0.45 nm that must be added even for this ultrathin effective gate dielectric.

The inset of Fig. 3(b) compares the centroid positions at 100C and 25C for the undoped body case. For stronger confinement, the centroid is approximately 0.1 nm closer to the interface at 25C (device characterization temperature) than

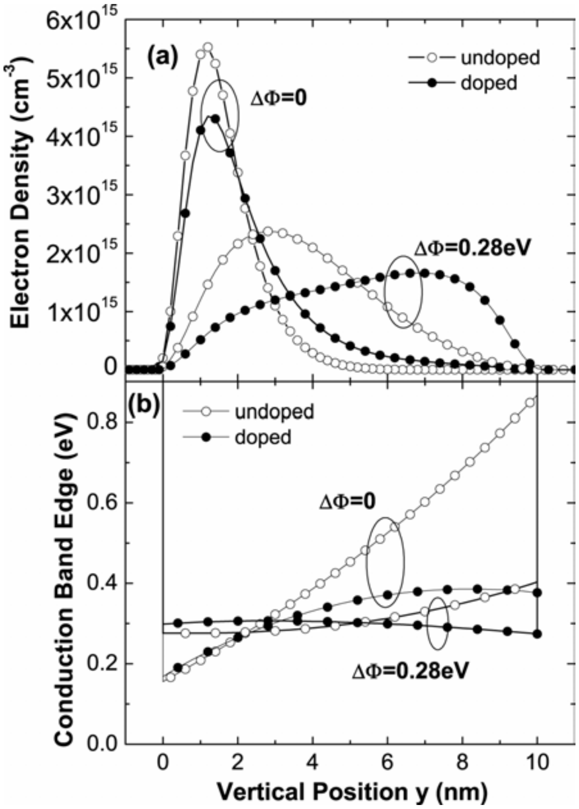


Fig. 4. Comparison of the (a) electron distribution and (b) confining potentials to achieve the same off-current, generated by applied back gate voltage and channel doping for gate work function shifts of ΔΦ =0 and ΔΦ=0.28eV.

at 100C (typical worst-case operating temperature). As the confinement is reduced, the temperature dependence weakens and may even reverse, as for ΔΦ=0.42 eV.

Despite achieving the same I_{off} target, back gate bias and channel doping generate somewhat different confinement potentials and electron distributions, as compared in Fig. 4(a-b) for band-edge and quarter-gap work functions. In the absence of two-dimensional effects and substantial inversion charge, we expect from Poisson's equation the potential along a vertical cut to vary linearly for the undoped body and quadratically for the doped body. For ΔΦ=0, the potential approximately follows this dependence, resulting in weaker confinement for the doped body. For ΔΦ=0.28 eV, the loss of confinement for the doped case is even more pronounced than for the undoped case. We note that although the stronger confinement provided by the back gate benefits the gate-channel coupling, the steep rise in confining potential, as for ΔΦ=0, can also lead to an undesirable buildup of holes near the back interface.

III. CONCLUSION

Although metal gates offer potential for continuing device scaling, loss of confinement for in-gap work functions is a serious concern that must be accounted for in realistic device design. Particularly in the off-condition, this loss of confinement causes the weak inversion layer to broaden and move away from the top interface, reducing the gate-channel capacitance and degrading the short-channel behavior. In a thin SOI device the confinement is aided by the back interface, but an SOI thickness less than the 10 nm of this study would be necessary to offset the effects. The confinement degradation is worse when conventional channel doping is used compared to back gate bias with an undoped body. An effectively thinner gate insulator using a high-κ material can help, but this study suggests that, even with a band-edge metal, carrier confinement in the off-condition will limit the scaling benefits.

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