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Comment

Comment on ‘Germanium electron–hole bilayer tunnel field-effect transistors with a symmetrically arranged double gate’

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Abstract

In this comment we demonstrate that the inclusion of field-induced quantum confinement effects through appropriate discretization of conduction and valence bands refutes the suitability of a germanium electron–hole bilayer tunnel field-effect transistor with symmetrically arranged gates (Jeong *et al* 2015 *Semicond. Sci. Technol.* **30** 035021). Delayed alignment of the first electron and hole energy subbands in the central gated intrinsic channel region makes the onset of vertical band-to-band tunneling unattainable at low applied voltages for the metal workfunctions used by Jeong *et al*. Furthermore, quantization effects lead to the appearance of unavoidable parasitic lateral tunneling to the lightly doped drain-source region (LDD), which seriously degrades the switching behavior reported by Jeong *et al*.

Keywords: band-to-band tunneling, quantum confinement, electron–hole bilayer tunnel field-effect transistor, symmetric double gate

(Some figures may appear in colour only in the online journal)

In their paper [1], Jeong *et al* tackle the inclusion of field-induced quantum confinement effects in the proposed symmetric electron–hole bilayer tunnel FET through the consideration of a properly calibrated density gradient model. However, this model disregards the fact that, as a result of sharpened band profiles arising from bilayer structures, conduction and valence bands turn into discrete sets of energy levels with their classical edges being states no longer allowed [2]. Ignoring this crucial aspect impeded the authors from realizing in their study that the main drawback of their suggested structure is that the intrinsic and the LDD regions are affected differently by subband quantization. As a result, weaker confinement effects in the LDD regions trigger unwanted lateral tunneling at top gate voltages (V_{G1}, following the authors’ notation), lower than those required to attain the desired onset of vertical tunneling in the intrinsic region (where confinement effects are stronger).

We simulated the structure depicted in figure 1 [1] following the simulation approach described in [3] through a customized hybrid integration that combines the best capabilities of the most recent versions of the widely used TCAD simulators Silvaco ATLAS (v.5.20.2.R) [4] and Synopsys Sentaurus (v.2014.09) [5]. Discretization of conduction and valence bands is implemented by modifying their profiles via editor structure tools to make them coincident with their first bound states, hence enabling BTBT to occur between the first subbands, and not between band edges as found by Jeong *et al*. This TCAD-based bandgap widening was originally proposed for TFETs where the BTBT phenomena and gate electric field directions were not aligned [6]; and later extended for the case of aligment with a 1D band structure

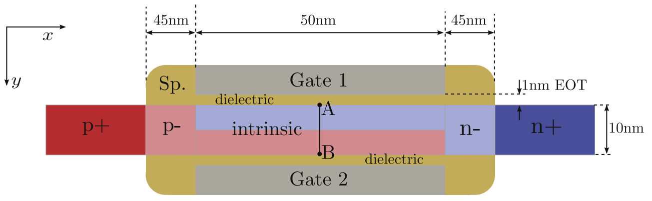

Figure 1. Schematic cross-section (not to scale) of the symmetric Ge EHBTFET considered by Jeong *et al*. The segment $\overline{AB}$ stands for a vertical cut at the center of the intrinsic gated region.

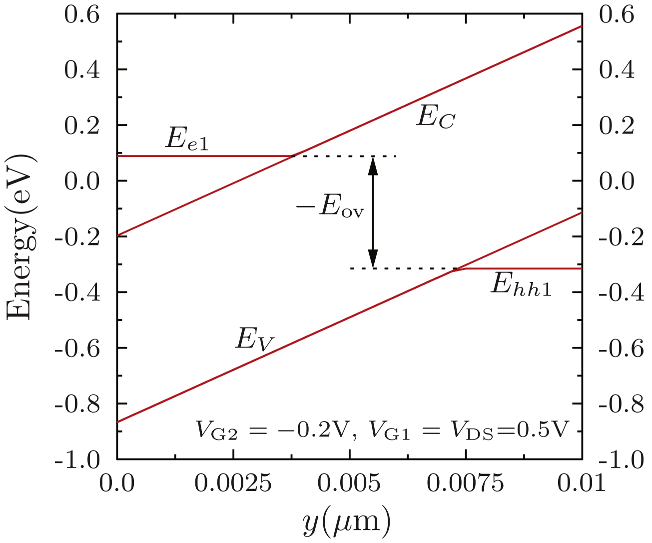

Figure 2. Band profile along the segment $\overline{AB}$ for $V_{DS} = V_{G1} = 0.5$ V and $V_{G2} = -0.2$ V. The negative energy overlap between electron and hole first subbands prevents vertical BTBT from being triggered.

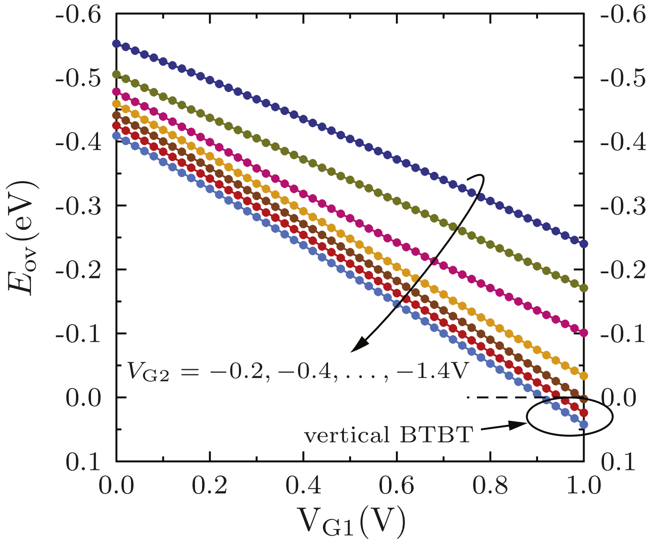

Figure 3. Energy overlap between first electron and hole subbands along $\overline{AB}$ as a function of the applied V_{G1} for different negative V_{G2} biases.

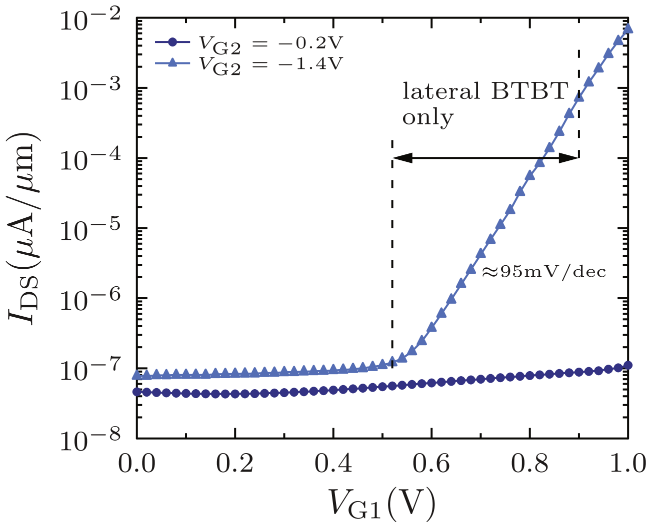

Figure 4. Transfer characteristics for the germanium EHBTFET with symmetrically arranged gates. Observe that for the biasing proposed by Jeong *et al* ($V_{G2} = -0.2$ V and $V_{DS} = 0.5$ V), the device remains at the OFF-state for the entire V_{G1} ramping; whereas for $V_{G2} = -1.4$ V the appearance of parasitic lateral tunneling provides degraded switching behavior for $V_{G1} > 0.52$ V.

modification [7], or with a more accurate 2D bandgap adjustment [3]. Very recently, quantization bandgap widening effects for pocketed dual-metal-gate TFETs have been assessed using a very similar technique [8].

In figure 2, we show the band profile across the channel along the segment $\overline{AB}$ of figure 1 for $V_{G1} = 0.5$ V, $V_{G2} = -0.2$ V, $V_{DS} = 0.5$ V and the workfunctions used by Jeong *et al*, $\phi_{G1} = 4.0$ eV and $\phi_{G2} = 4.66$ eV. According to [1], for this polarization the proposed device should be at the ON-state with vertical BTBT enabled. However, we observe that when subband discretization is considered, the first electron and hole bound states, E_{e1} and E_{hh1}, are still far from being aligned (negative energy overlap).

Moreover, for the structure proposed by Jeong *et al*, subband alignment along $\overline{AB}$ is only attained at $V_{G1} \leqslant 1.0$V when $|V_{G2}| \geqslant 1.0$ V, as illustrated in figure 3; whereas much weaker confinement effects in the LDD region would allow parasitic lateral BTBT processes to flow from the intrinsic region to it. This irremediably degrades the transfer characteristic of this type of EHBTFET by increasing current levels at the OFF-state and fading the apparent steep slope behavior derived from semiclassical simulations and reported in [1]. Figure 4 shows that for $V_{G2} = -0.2$ V neither vertical nor lateral BTBT are allowed for $V_{G1} \leqslant 1$ V. Conversely, if we apply $V_{G2} = -1.4$ V, we observe that for $V_{G1} > 0.52$ V lateral tunneling appears providing a subthreshold swing of ≈95 mV/dec; which in turn masks the steep slope that, otherwise, would be observed for $V_{G1} > 0.9$ V according to figure 3.

With this comment, we aimed to emphasize how important an adequate treatment of confinement effects in bilayer tunneling transistors may be for assessing the feasibility or, as in this case, unfeasibility of certain potentially interesting structures.

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