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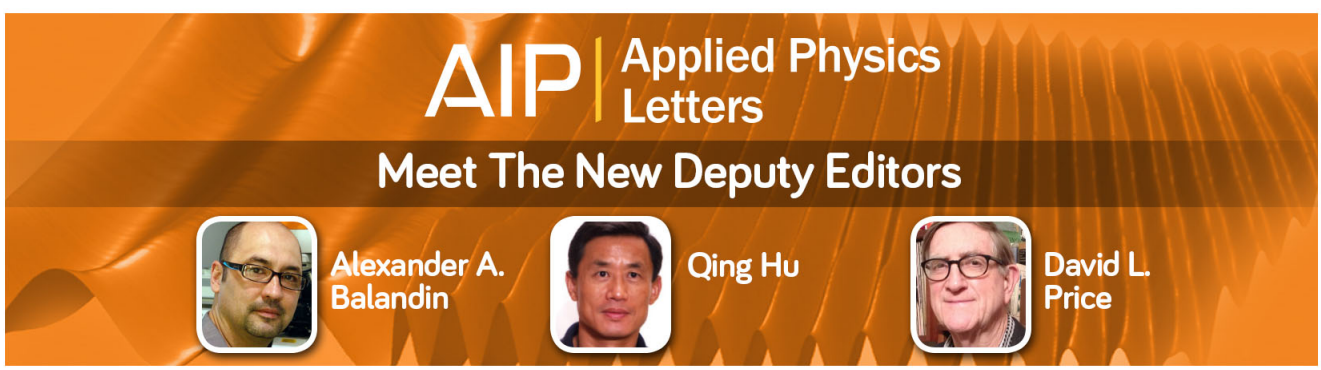

Response to "Comment on 'Assessment of field-induced quantum confinement in heterogate germanium electron–hole bilayer tunnel field-effect transistor'" [Appl. Phys. Lett. 106, 026102 (2015)]

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In our letter,[1] we demonstrated that the inclusion of field-induced quantum confinement in the analysis of the Ge Electron–Hole Bilayer Tunnel Field–Effect Transistor (EHBTFET) led to the appearance of undesired lateral tunneling which degraded the so far reported outstanding switching behavior of these devices.[2] We showed that a heterogate configuration (HG-EHBTFET) with different workfunctions for the overlap and underlap sections of the top gate, ϕ_{tg1} and ϕ_{tg2}, respectively (see Fig. 1(c) in Ref. 1), proved to be appealingly efficient to suppress this parasitic tunneling at $V_D = 0.5$ V and restore the steepness of the $I_D - V_{TG}$ curves. The main point of the comment raised by Hsu *et al.*[3] was to elucidate the potential drawbacks that the proposed work function difference might cause at low drain voltages. They showed that no deleterious effects arise in that scenario by analyzing the electron eigenenergy difference for the first subbands in the overlap and underlap regions, ΔE, for $V_D < 0.5$ V and concluded that a heterogate configuration is also quite advisable at low V_D. Furthermore, they showed (Fig. 1(b) in Ref. 3) that there exists an optimized value of ϕ_{tg2} for which ΔE turns out to be approximately independent of V_D. Our response seeks to explain the interesting behavior of the $\Delta E(V_D)$ curves depicted in Fig. 1(b) of the comment by Hsu *et al.*[3] for better understanding of the effect that heterogate configuration has on the performance of these devices. The results herein presented were obtained employing the simulation approach used in our original letter[1] with the device structure considered by Hsu *et al.*[3]

First, the increasing behavior of ΔE at very low V_D for $\phi_{tg2} = 4.3$eV (Ref. 3) is due to the tighter control that the drain exerts over the first electron subband in the overlap, $E_{e1,OL}$ compared to that in the underlap, $E_{e1,UL}$, as seen in Fig. 1 where we plot the derivative of E_{e1} with respect to V_D. Second, the almost constant behavior of ΔE for $\phi_{tg2} = 4.2$eV (Ref. 3) follows from the similar pattern of the $E'_{e1}(V_D)$ curves in both regions. Third, the saturation of the decreasing pattern of ΔE observed for $\phi_{tg2} = 4.1$eV (Ref. 3) that starts at $V_D \approx 0.18$V comes from the depinning of $E_{e1,UL}$. As displayed in the inset, we can estimate the point at which this depinning takes place by means of the maximum

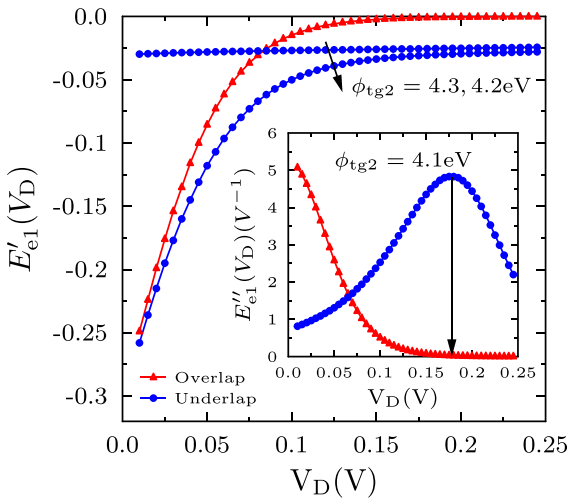

FIG. 1. First derivative and second derivative (inset) of the energy of the first subbands for electrons as a function of the drain voltage in both overlap and underlap regions corresponding to the structure depicted in Fig. 1(a).[3]

of second derivative[4] of $E_{e1}(V_D)$ and confirm that it occurs at a value of $V_D = 0.18$V. For $V_D > 0.18$V the depinning implies that the top gate recovers the control over $E_{e1,UL}$ and therefore when we increase ϕ_{tg2} by 0.2 eV from 4.1 to 4.3 eV, ΔE behaves practically likewise (Fig. 1(b) in Ref. 3).

This response complements the pertinent comment by Hsu *et al.*[3] reinforcing the HG-EHBTFET reliability at low drain voltages and provides an explanation for the observed behavior of the eigenenergy difference between the first bound states for electrons in the overlap and underlap regions when increasing ϕ_{tg2}.

[1]J. L. Padilla, C. Alper, F. Gamiz, and A. M. Ionescu, Appl. Phys. Lett. **105**, 082108 (2014).
[2]L. Lattanzio, L. De Michielis, and A. M. Ionescu, IEEE Electron Device Lett. **33**, 167 (2012).
[3]W. Hsu, J. Mantley, L. F. Register, and S. K. Banerjee, Appl. Phys. Lett. **106**, 026102 (2015).
[4]J. L. Padilla, F. Gamiz, and A. Godoy, IEEE Trans. Electron Devices **59**, 3205 (2012).

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