Silicon-compatible high-hole-mobility transistor with an undoped germanium channel for low-power application

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Silicon-compatible high-hole-mobility transistor with an undoped germanium channel for low-power application

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In this work, Ge-based high-hole-mobility transistor with Si compatibility is designed, and its performance is evaluated. A 2-dimensional hole gas is effectively constructed by a AlGaAs/Ge/Si heterojunction with a sufficiently large valence band offset. Moreover, an intrinsic Ge channel is exploited so that high hole mobility is preserved without dopant scattering. Effects of design parameters such as gate length, Ge channel thickness, and aluminum fraction in the barrier material on device characteristics are thoroughly investigated through device simulations. A high on-current above 30 μA/μm along with a low subthreshold swing was obtained from an optimized planar device for low-power applications. © 2013 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License. [http://dx.doi.org/10.1063/1.4833295]

Germanium (Ge) is a material with versatility in both electronics and photonics due to its relatively high electron mobility (≤3900 cm²/V·s) compared with that of silicon (Si) (≤1500 cm²/V·s) and its peculiar energy-band structure in that a local conduction band (E_C) minimum exists at the Γ valley (k = 0 in the momentum space).1 Because of these virtues, Ge has been adopted for a wide range of applications in high-speed electronic devices and group-IV-based optical components.2–6 Another merit of Ge is found in its prominently high hole mobility among the most prevalent semiconductors used for functional devices as shown in Table I.1,7–9

<table>
<thead>
<tr>
<th>Si</th>
<th>GaAs</th>
<th>InAs</th>
<th>InP</th>
<th>GaN</th>
<th>SiC</th>
<th>Ge</th>
</tr>
</thead>
<tbody>
<tr>
<td>450</td>
<td>400</td>
<td>500</td>
<td>200</td>
<td>300</td>
<td>100</td>
<td>1900</td>
</tr>
</tbody>
</table>

Although the smaller energy bandgap (E_g = 0.8 eV at the Γ valley and 0.66 eV at the L valley) of Ge offers the opportunity for the effective quantum confinement of holes to form 2-dimensional hole gas (2DHG) due to its large valence band offset (ΔE_V = 0.834 + 0.147x, where x is Al fraction in AlGaAs for x < 0.45).18 At the same time, Ge has higher graftability to Si, which realizes monolithic integration on a Si platform with advanced electronic devices and optical components.6,19,20

In the present study, a high-hole-mobility transistor (HHMT) with an undoped Ge channel is designed and characterized by device simulation.10–12 By using an intrinsic Ge channel, there is no loss in hole mobility owing to dopant scattering, and the leakage current by band-to-band tunneling between the channel and drain is significantly reduced. Following the configuration of conventional metal-semiconductor field-effect transistors (MESFETs), the high-χ dielectric used as the gate oxide in Ge MOSFETs is replaced by an AlGaAs epitaxial layer due to its small lattice mismatch with Ge, which greatly simplifies the fabrication by eliminating complicated steps for gate oxidation which substantially reduces the mobility degradation owing to surface scattering.17 Moreover, the AlGaAs/Ge heterojunction is an ideal structure for the effective quantum confinement of holes to form 2-dimensional hole gas (2DHG) due to its large valence band offset (ΔE_V = 0.834 + 0.147x, where x is Al fraction in AlGaAs for x < 0.45).18 At the same time, Ge has higher graftability to Si, which realizes monolithic integration on a Si platform with advanced electronic devices and optical components.6,19,20

Figure 1(a) shows the schematic a real view of the simulated Ge HHMT. Gate length (L_G), Ge channel thickness (T_Ge), and aluminum (Al) fraction have been treated as the device variables. Al (work function = 4.06 eV) was used for the gate metal. The p-type Si substrate had a doping concentration of 10^{19} cm^{-3} and p source and drain were doped at 10^{19} cm^{-3}. The p^+ AlGaAs barrier had a thickness of 30 nm, and its doping concentration was 10^{18} cm^{-3}. For higher accuracy in the simulation, multiple models including field- and concentration-dependent models, a Shockley–Read–Hall recombination model, and a quantum model were activated in cooperation. Figures 1(b) and 1(c) demonstrate the simulated energy-band diagrams in the vertical (at the device center) and lateral (across the Ge channel) directions, respectively. In each figure, the upper and lower parts show

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diagrams in the off- and on-states (off-state: \( V_{GS} = 1.0 \) V, \( V_{DS} = 0 \) V; on-state: \( V_{GS} = V_{DS} = 1.0 \) V). It is assured from the figures that the band arrangement for effective hole confinement is not interrupted in any circumstance, and that the energy barrier seen by the free holes is completely lowered by an operation voltage as small (in magnitude) as \( 1.0 \) V.

Figure 1(d) illustrates the hole current density obtained by simulation in a magnified view of the intrinsic Ge channel, by which the formation of 2DHG is more tangibly confirmed. From a fabrication point of view, it might be a tricky task to achieve seamless interfacing of the heterojunctions in the HHMT and Ge/Si interface should be more challenging than AlGaAs/Ge site since the lattice mismatch between Ge and Si (4%) is much larger than that between AlGaAs and Ge (within 0.08%). However, it is a relieving feature that the conduction carriers of the HHMT are drifted along the AlGaAs/Ge interface away from Ge/Si interface in its drive mode, and further, a permissibly smooth relaxed Ge/Si interface can be also obtained by a cyclic epitaxy technique combining low-temperature growth and flash annealing.

Figures 2(a)–2(c) show the electrical performances of a Ge HHMT with varying \( L_G \) from 500 nm down to 20 nm with other design variables fixed at \( T_{Ge} = 10 \) nm and Al fraction = 0.3. Figures 2(a) and 2(b) depict the transfer and output characteristics of a device with \( L_G = 200 \) nm. In the transfer curves, it is observed that gate-induced drain leakage (GIDL) by band-to-band tunneling is effectively suppressed, and a steep subthreshold slope (SS) is obtained. Subthreshold swing (\( S \)) is defined as the reciprocal of the maximum instantaneous SS (in absolute value), \( S = \frac{|d \log I_D/d V_{GS}|_{\text{max}}}{V_{GS}} \), as illustrated in the inset. The extracted \( S \) under the given condition was less than \( 80 \) mV/dec. The output curves are similar to typical curves of p-type MOSFETs (PMOSFETs) and evenly spaced by \( V_{GS} \). Figure 2(c) illustrates collectively the direct-current (DC) parameters as functions of \( L_G \). The on-state current (\( I_{on} \)) shows a monotonic increase, while \( S \) is degraded as \( L_G \) is scaled down, where \( S \) values are checked only at the high drain voltage (\( V_{DS} = 1.0 \) V). Threshold voltage (\( V_{th} \)) becomes positively higher, and drain-induced barrier lowering (DIBL) increases as \( L_G \) shrinks. 

\( V_{th} \) was defined by the constant-current method at a reference \( I_D \) of \( I_{Ref} = 10^{-7} \) A/\( \mu m \), and DIBL was extracted mathematically from the amount of \( V_{th} \) shift normalized by the \( V_{DS} \) change (in

FIG. 1. Device configurations. (a) Areal view of the simulated device. (b) Energy-band diagrams at the device center in the vertical direction (upper: off-state, lower: on-state). (c) Energy-band diagrams along the channel beneath the AlGaAs/Ge interface (upper: off-state, lower: on-state). (d) Formation of 2DHG at the on-state, \( V_{GS} = V_{DS} = 1.0 \) V.

FIG. 2. Electrical characteristics as a function of \( L_G \). Validation of Ge HHMT by (a) transfer and (b) output characteristics from a device with \( L_G = 200 \) nm, \( T_{Ge} = 10 \) nm, and Al fraction = 0.3. (c) DC parameters as a function of \( L_G \): \( I_{on} \) and \( S \) (upper); \( V_{th} \) and DIBL (lower) (\( T_{Ge} = 10 \) nm, Al fraction = 0.3).
absolute value), DIBL = \left| \frac{\Delta V_{th}}{\Delta V_{DS}} \right| = \left| \frac{V_{th} - V_{th0}}{V_{DS} - V_{DS0}} \right| = 1.0 V - V_{th1}/V_{DS} = -50 mV/[1.0 V - (-50 mV)] (unit in V/V), as indicated in Fig. 2(a). Although further device optimization by geometrical rendering into a fin-shaped-channel FET (FinFET), double-gate (DG) or multiple-gate (MuG) FET, a nanowire FET would produce improvements in S and DIBL, 22–29 and it is an encouraging fact that high current drivability reaching some tens of amperes per unit width has been obtained from an unaltered in-plane Ge HHMT.

Figures 3(a)–3(c) illustrate the DC parameters for varying $T_{Ge}$ from 5 nm to 100 nm keeping the other variables constant at $L_G = 200$ nm and Al fraction $= 0.3$. Figure 3(a) depicts $I_{on}$ and current ratio ($I_{on}/I_{off}$, $I_{off}$: off-state current) as a function of $T_{Ge}$. $I_{on}$ shows a monotonic increase with $T_{Ge}$ but the extremely thin channel below 10 nm needs to be avoided to secure sufficient current drivability. It is noticeable that the change in $I_{on}$ by modulating $T_{Ge}$ over 100 nm is much larger than that by $L_G$ scaling over 500-nm range, which implies that controlling $T_{Ge}$ is more steering factor in determining the current drivability of Ge HHMT. However, the current ratio decreases with increasing $T_{Ge}$, and $T_{Ge}$ should be kept thin below the upper limit to obtain a high current ratio. The trade-off relation between $I_{on}$ and current ratio implies that a large portion of optimal design should be placed on $T_{Ge}$. $S$ is plotted as a function of $T_{Ge}$ in Fig. 3(b). To obtain a small swing (tentatively, with a reference of 100 mV/dec), $T_{Ge}$ needs to be kept thin below 40 nm. This supports that the swing characteristics of Ge HHMT would be superior to those of Ge PMOSFETs fabricated on Ge bulk substrate. Along with $S$, $I_{off}$ can also play a role as an index of gate controllability in a thin-body electron device. Figure 3(c) depicts $I_{off}$ as a function of $T_{Ge}$. $I_{off}$ is linearly scaled with $T_{Ge}$ since $I_{off}$ would be proportional to the area (device width (constant $= 1 \mu m$) $\times T_{Ge}$) normal to hole flux assuming that the gate has complete controllability over the thin Ge channel, which leads to a plot of $I_{off}$ as a linear function of $T_{Ge}$. $I_{off}$ increases with $T_{Ge}$ linearly up to $T_{Ge} = 30$ nm; however, the plot shows a hyperlinear trend above that thickness, as indicated by the linear and actual lines in Figure 3(c). It is implied that $T_{Ge}$ needs to be falling into the permissible range (green box in the figure) in order to have a strong gate controllability over the channel. Considering the overall results, $T_{Ge}$ is a crucial design variable that should be optimally determined, possibly with a permissible range of $T_{Ge} = 10$ nm to 30 nm, for higher current drivability and strong gate controllability.

Figures 4(a)–4(c) demonstrate the effects of the Al fraction in the AlGaAs barrier material on the current characteristics of the Ge HHMT. The other variables were kept constant at $L_G = 200$ nm and $T_{Ge} = 10$ nm. Compared with the previous two design variables, the Al fraction has a relatively small effect on the device performance. The change in $I_{on}$ was as small as $2 \mu A/\mu m$, and the current ratio also showed a small change of $10^5$, which is below a percent order change compared with the base value of $10^5$ over the full sweep of the Al fraction from 0 to 1, as shown in Figure 4(a). $S$ is also almost invariant with the Al fraction, as shown in Figure 4(b), where the change in $S$ is found to be only $3 mV/\text{dec}$ by the full scaling of the Al fraction. A relatively more distinguishable change is observed by modulating the Al fraction in the $V_{th}$ shift, as plotted in Figure 4(c). However, its effect on $V_{th}$ is still smaller than that of another variable, $L_G$. These results ensure that the electrical performance of the Ge HHMT has a strong tolerance against deviation in the Al fraction that might occur during the epitaxy process; this is another advantage of the device, even from a more practical point of view.

We optimally designed a silicon-compatible AlGaAs/Ge/Si heterojunction HHMT considering the channel length, channel thickness, and Al fraction of the barrier. It has been confirmed that an effective quantum confinement of holes forming a 2DHG was achieved by the material system, which confirms the feasibility of the device for low-power applications. Improved reliability, simpler fabrication, higher current drivability that eliminates both dopant and surface scattering, and stronger process tolerance make the Ge HHMT favorable and highly competitive with conventional Si CMOS and Ge PMOSFETs.

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18J. S. Harris, Jr., *Class Notes from EE327 Properties of Semiconductor Materials* (Stanford University, 2013).


