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Drive Current Enhancement with Invasive Source in Double Gate Tunneling Field-Effect Transistors

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1. Introduction

Tunneling field-effect transistor (TFET) is one of the promising alternatives to overcome CMOS subthreshold limitation of 60 mV/decade at room temperature. It exploits the band-to-band tunneling (BTBT) phenomenon to achieve steep subthreshold swing (SS) and high I_{on}/I_{off} ratio at ultra low supply voltage V_{DD}. However, existing Si, Ge, or III-V TFETs suffer from low drive current and many efforts are directed at improvement of the ON-state current with the use of hetero-junction and advanced multi-gate device architecture [1]-[7].

In this work, we perform a simulation study of novel source structures for enhancement of the ON-state current for double-gate (DG) Ge TFETs and Ge-source Si-body TFETs. By employing an invasive source structure, the p^+ region in the middle of the channel extends under the gate, and high electric field ξ extends into the middle of the channel. More tunneling paths with shorter lengths can be found in the ON-state, boosting the drive current.

2. Parameters Definition and Methodology

The device simulation was performed using our in-house 2D TCAD simulator which implements a physics-based non-local BTBT algorithm [8]. A box-like abrupt source-channel junction was used in our simulation, and the key parameters are listed in Fig. 1. I_{off} is extracted at V_{ds} = 0.8 V and V_{gs} = 0 V while I_{on} at V_{gs} = 0.8 V and V_{ds} = 0.6 V. The average SS is calculated from $I_{ds} = 10^{-9}$ mA/μm to 10^{-3} mA/μm. Strain effects are not considered.

3. Device Simulation and Discussion

A. Σ-shape invasive source Ge TFETs

Fig. 1 shows the structure and doping profile of Σ-shape invasive source Ge TFET and a control TFET. Simulated tunneling paths and BTBT-generated carrier density are also shown. At a fixed ON-state bias, more tunneling paths can be found in Σ-shape source TFET than the control device. Fig. 2 compares the ξ-field distribution in two devices, showing the presence of an extensive high field region in the Σ-source TFET. In the Σ-source TFET, significant BTBT occurs with the origin of tunneling found near the middle of the channel, where the high field contributes to short tunneling paths. It should be noted that although the ξ-field is rather high at the gate edges of both devices, it does not contribute much to the tunneling current since the surface band bending is not larger than bandgap E_G to allow BTBT.

Fig. 3 shows that Σ-source TFETs have higher I_{on} than the control TFET, for a given I_{off}. The I_{on} enhancement is due to the increased number of short tunneling paths. I_{on} increases with increasing source extension length L_{extend}, which is due to the larger tunneling region under the gate.

B. Si-body TFETs with Σ-shape Ge-source

TFETs with Ge-Si hetero-junction can achieve very low I_{off} and improved SS [9], and will be investigated further here. Si-body TFETs with Σ-shape Ge-source is simulated using device parameters listed in Fig. 1. The gate work function is adjusted to achieve the same tunneling onset gate voltage. Fig. 4 shows the device structure and band diagrams near the surface, and the corresponding *I-V* curves are presented in Fig. 5. I_{off} can be reduced by ~100× by incorporating the Ge-Si hetero-junction, as compared with a all-Ge TFET. The Si-body TFET with Ge-Σ-source and L_{extend} = 10 nm achieves a higher I_{on} and a reduced SS in comparison with the control Ge TFET.

C. Comparison among different shapes of invasive sources

Ge TFETs with invasive sources of different shapes are shown in Fig. 6, and the corresponding *I-V* curves are shown in Fig. 7. The arc-shaped source (Source② in Fig. 6), which can be formed by recess etch and Ge epitaxy with *in situ* doping, has a smaller I_{on} enhancement over the control, as compared with other source designs. The device with squarish invasive source (Source③ in Fig. 6) gives the largest I_{on} due to the high ξ-field at the 2 corners.

The application of Ge-Si heterojunction is considered next. Si-body TFETs with circular and squarish invasive Ge source are also studied, as shown in Fig. 8. The most optimized structure, Ge-source③ Si-body, gives drain current of more than 1 mA/μm at $V_{ds} = V_{gs}$ = 0.8 V. Fig. 9 summarizes the I_{on}, I_{off}, and SS of TFETs with invasive sources of different shapes. It is observed that performance is increased with a larger L_{extend}.

4. Conclusion

We studied the dependence of TFET performance on source design using a 2D TCAD simulation tool. Use of an invasive source with an optimized shape could be used to realize an increased tunneling region, giving a higher I_{on}. Applying the invasive source in Ge-source Si-body TFET can further enhance the device performance.

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References

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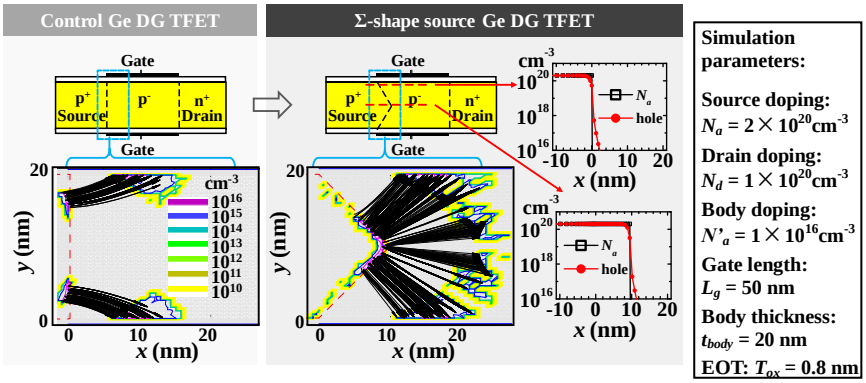

Fig. 1. Device structures of control Ge TFET and Σ-source Ge TFET. BTBT generated carrier density and tunneling paths (V_{ds} = 0.8 V, V_{gs} = 0.2 V) are shown, where dominant tunneling paths that contribute to 40% of the total current are plotted. The doping profile and hole concentration are shown at surface and middle cutlines .

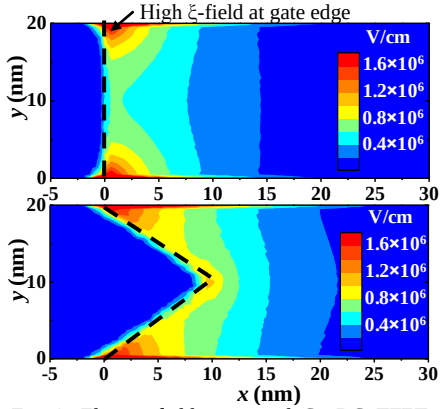

Fig. 2. Electric field in control Ge DG TFET (upper plot) and in Σ-source Ge DG TFET (lower plot) at V_{ds} = 0.8 V and V_{gs} = 0.2 V. The black dashed lines are source-channel edges.

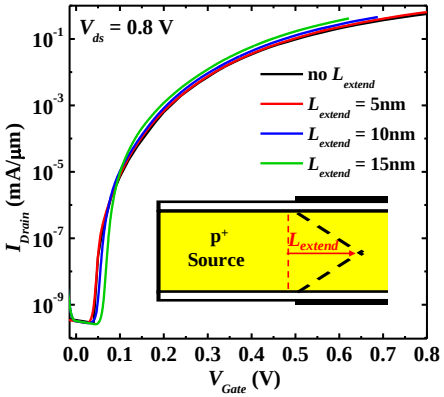

Fig. 3. I-V characteristics of Σ-source Ge TFETs with various lengths of extension length (L_{extend}).

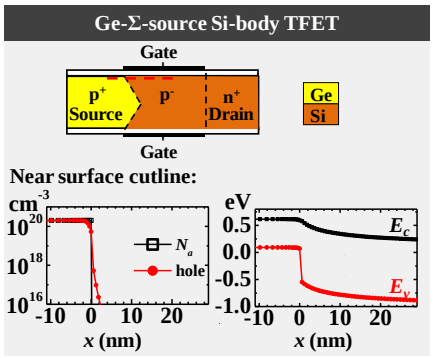

Fig. 4. The structure of Ge- Σ-source with Si-body DG TFET. For the near surface cutline, the doping profile and hole concentration are shown on the left, while the band diagram of Ge-Si hetero-junction are shown on the right.

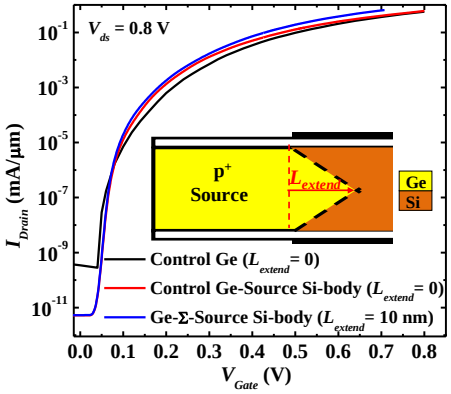

Fig. 5. I-V characteristics of control Ge TFET, control Ge-source Si-body TFET and Ge-Σ-source Si-body TFETs with L_{extend} = 10nm.

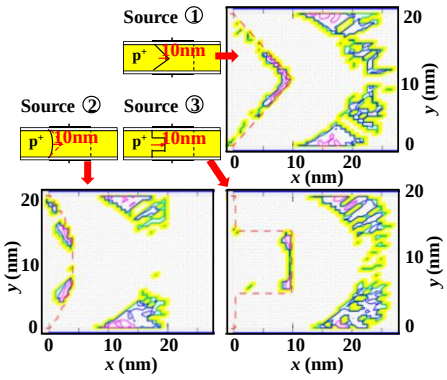

Fig. 6. Band-to-band generation rate contour of Ge-TFETs with three different kinds of invasive-source: ① Σ-shape; ② circular-shape; ③ squarish-shape at V_{ds} = 0.8 V and V_{gs} = 0.2 V. The legend is the same as Fig. 1.

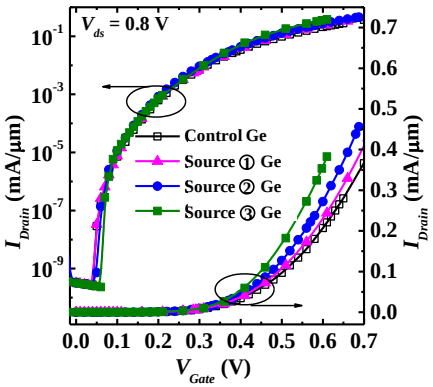

Fig. 7. I-V characteristic of Ge DG TFETs with three different kindsinvasive source structures. Source①, Source② and Source③ refer to the invasive Source①, Source② and Source③ in Fig. 6.

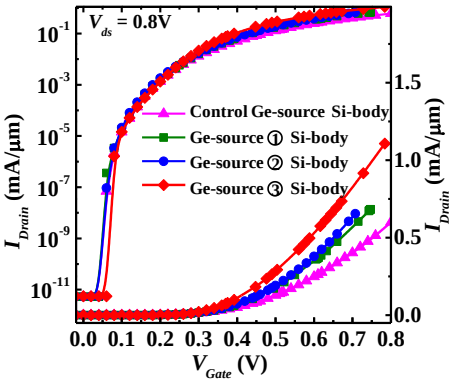

Fig. 8. I-V characteristic of Ge-source Si-body TFETs with three different kinds of invasive-Ge-source structures. Source①, Source② and Source③ refer to the invasive Source①, Source② and Source③ in Fig. 6.

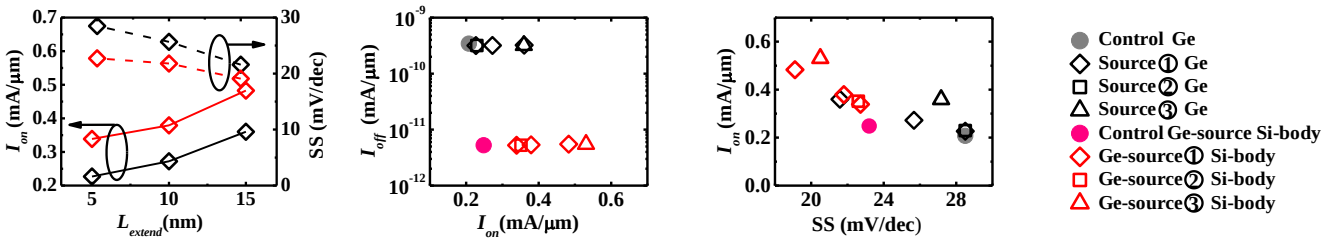

Fig. 9. Summary of invasive source TFETs performance: I_{on} / SS at various L_{extend}, I_{off} vs I_{on} and I_{on} vs *S.S.* for proposed recess source TFETs.