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Strained-Si$_{1-x}$Ge$_x$/Si Band-to-Band Tunneling Transistors: Impact of Tunnel-Junction Germanium Composition and Doping Concentration on Switching Behavior

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Abstract—Strained pseudomorphic Si/Si$_{1-x}$Ge$_x$/Si gate-controlled band-to-band tunneling (BTBT) devices have been analyzed with varying Ge composition up to 57% and p+ tunnel-junction (source) doping concentration in the 10$^{19}$–10$^{20}$ cm$^{-3}$ range. Measurements show the impact of these parameters on the transfer and output characteristics. Measurements are compared to simulations using a nonlocal BTBT model to analyze the mechanisms of device operation and to understand the impact of these parameters on the device switching behavior. The measured characteristics are consistent with simulation analysis that shows a reduction in energy barrier for tunneling ($E_{get}$) and a reduction in tunneling distance with increasing Ge composition and source doping concentration. Increases in the pseudomorphic layer Ge content and doping concentration of the tunnel junction produce large improvements in the measured switching-behavior characteristics ($I_{on}$, slope, turn-on voltages, and sharpness of turn-on as a function of $V_{dd}$); Simulations are also performed to project the potential performance of more optimized structures that may be suitable for extremely low power applications ($V_{dd} < 0.4$ V).

Index Terms—Band-to-band tunneling, strained SiGe, switching, transistor, tunnel-transistor.

I. INTRODUCTION

LOGIC switch devices that operate based on band-to-band tunneling (BTBT) are considered as candidates for extremely low voltage operation (< 0.4 V) due to the potential for sub-60-mV/dec swing (at room temperature) over part of their current switching characteristic [1]–[8]. Efficient devices with a large-$J_{on}/I_{off}$ ratio at low-$V_{dd}$ operation will require very low energy barrier for tunneling, sharp and high tunnel-junction doping concentration, and small effective gate-insulator thickness [8]. Recent measurements of strained-Si$_{0.6}$Ge$_{0.4}$ gated diodes with $E_g = 0.7$ eV have demonstrated a significant enhancement in the gate-controlled tunneling current relative to coprocessed silicon control devices due to the narrow-bandgap material [7]. Moreover, the insensitivity of the measurements to temperature in the 77-K–300-K range and the agreement with simulation using a quantum–mechanical BTBT model confirmed the gate-controlled BTBT-based device operation in strained-SiGe devices [7]. In order to potentially improve the switching characteristics of tunneling FETs (TFETs), increased junction doping level and reduced energy barrier for tunneling are expected to be required. In this paper, strained-Si$_{1-x}$Ge$_x$/Si gate-controlled BTBT devices have been analyzed with varying Ge composition up to 57% and p+ tunnel-junction (source) doping concentration in the 10$^{19}$–10$^{20}$ cm$^{-3}$ range to study directly the impact of these parameters on the measured transfer and output characteristics. The measured results are consistent with simulation analysis that shows a reduction in energy barrier for tunneling ($E_{get}$) and a reduction in tunneling distance with increasing Ge composition and source doping concentration. Increases in the SiGe layer Ge content and doping concentration of the tunnel junction produce large improvements in the measured switching-behavior characteristics ($I_{on}$, slope, turn-on voltages, and sharpness of turn-on as a function of $V_{dd}$). Although the test structures analyzed were part of another experiment [9], [10] and were not specifically optimized to achieve the desired goals of a low-$V_{dd}$ TFET technology, showing a maximum current of 8 μA/μm and a local subthreshold slope (SS) of 280 mV/dec at a $V_{dd}$ of 5 V, the trends examined in this paper demonstrate key dependences on the measured transfer and output characteristics that suggest routes for further improvement.

II. DEVICE FABRICATION

The devices (Fig. 1) were fabricated previously, as discussed in [9] and [10], in a strained pseudomorphic SiGe-channel p-MOSFET process flow, with the source and drain p+/n diodes of high-mobility MOSFETs constituting the gated diodes under study. Although these structures are not optimized to maximize BTBT gate control or tunneling generation rates, they form a useful test structure for exploration of the gate-controlled tunneling physics in narrow-bandgap strained SiGe, which is relevant to TFET device technology. Starting substrates were 6-in Si n$^+$ (0.008–0.020-Ω·cm) wafers. A 2-μm-thick Si layer was first grown, with in situ PH$_3$ doping, to a level of 10$^{17}$ cm$^{-3}$. The strained-Si$_{1-x}$Ge$_x$ (0%, 43%, 60%...
Fig. 1. Device schematic: \(L_{gate} = 50\ \mu m\) and \(W = 10\ \mu m\). The source dimensions are \(L_{sd} = 6\ \mu m \times W_{sd} = 10\ \mu m\). When operated as a TFET, the n-type substrate serves as the drain, collecting the carriers generated by gate-induced BTBT.

Fig. 2. (Left) XTEM of the fabricated strained-Si\textsubscript{0.57}Ge\textsubscript{0.43} device in the channel region. (Right) SIMS and SRP data of the p+ source for various B implant doses. The highest dose implant achieved an active doping concentration of \(\sim 10^{20}\ \text{cm}^{-3}\) (limited by the 800-\(\degree\)C 10-s RTA).

and 57% Ge) channel layers were grown by chemical vapor deposition, followed by a thin epitaxial Si cap layer. The SiGe and Si cap layers were not intentionally doped but are expected to be autodoped to a level of approximately \(10^{17}\ \text{cm}^{-3}\). After MOSFET processing, the final structure had an unstrained-Si cap thickness of 3 nm, a gate SiO\textsubscript{2} thickness of 4 nm, and an n+ \textit{in situ} doped polysilicon gate. The gate oxide was grown at 600 \(\degree\)C. The device-fabrication process is discussed in further detail in [9] and [10]. The primary difference between the process described in [9] and [10] and the flow employed for the present devices is the use of a source/drain extension, i.e., the deep source/drain implant is separated from the gate region by an oxide spacer [11]. The p+ source/drain extension implant used under the oxide spacer in this paper was 10-keV B with varying dose (\(7 \times 10^{13} - 5 \times 10^{14}\ \text{cm}^{-2}\)). Ion implants were activated by rapid thermal annealing at 800 \(\degree\)C for 10 s. Si control wafers with similar doping profiles were coprocessed along with the SiGe epitaxial structures. Fig. 2 (left) shows a sample cross-sectional TEM of a strained-Si\textsubscript{1-x}Ge\textsubscript{x} device and (right) also shows SIMS/select-spreading-resistance (SRP) data of the vertical doping profiles of the tunnel junctions. A maximum active dopant concentration of \(\sim 10^{20}\ \text{cm}^{-3}\) is achieved for the highest dose implant. The doping gradient in these test structures is rather relaxed and is \(\sim 45\ \text{nm/dec}\). By fitting \(C-V\) profiles [12], [13] (Fig. 3), valence-band offsets \(\Delta E_v\)'s of 0.4 and 0.55 eV, respectively, corresponding to energy-gap values of 0.7 and 0.55 eV, which are much reduced compared to Si.

Fig. 3. Measured \(C-V\) profiles for devices with 43% and 57% Ge contents. The extracted valence-band offsets \(\Delta E_v\)'s are 0.4 and 0.55 eV, respectively, corresponding to energy-gap values of 0.7 and 0.55 eV, which are much reduced compared to Si.

III. DEVICE MEASUREMENTS

The measured transfer characteristics for devices that had 43% Ge concentration in strained-SiGe layers with varying B implant dose are shown in Fig. 4. Increased source (tunnel-junction) doping increases the current drive and improves the SS. \(L_{gate} = 50\ \mu m\) and \(W = 10\ \mu m\).

Fig. 4. Measured transfer characteristics for 43%-Ge-content devices with varying B implant dose. Increased dose increases the current drive of the devices and improves the SS. \(L_{gate} = 50\ \mu m\) and \(W = 10\ \mu m\).
The devices’ output characteristics exhibit a slow turn-on with \( V_{ds} \) modulation and a saturation of drain current with \( V_{ds} \). Increased source doping concentration improves the output characteristics of devices by reducing the turn-on voltage (with \( V_{ds} \)) and also by increasing the sharpness of turn-on (\( dI_d/dV_{ds} \)). Fig. 6 shows the measured transfer characteristics for devices with varying Ge content (0%, 43%, and 57%). Increasing the Ge content results in further increase in current drive (\( I_{on} \)), at the same biasing, and also reduction in the measured slope (SS), consistent with a reduction in \( E_{geff} \) with increasing Ge. Fig. 7 shows that increasing the Ge content also improves the turn-on characteristics with \( V_{ds} \) (apparent turn-on threshold and sharpness of turn-on). The 57%-Ge-content \( 4 \times 10^{15} \text{cm}^{-2} \)-dose device shows a drive current of 8 \( \mu A/\mu m \), an \( I_{on}/I_{off} \) ratio of \( \sim 10^6 \), and a minimum local SS of \( \sim 280 \text{mV/dec} \) at \( V_{ds} \) of 5 V. Although the measured characteristics of these test structures are far from the desired goals of a low-\( V_{dd} \) TFET device, the trends examined in this paper suggest that further improvements (which could enable lower \( V_{dd} \) operation) can be
expected with reduction in gate-dielectric EOT, sharper doping profiles, and further reduction in $E_{\text{geff}}$.

### IV. Device Simulations and Discussion

Device simulations are performed using the nonlocal tunneling model offered in the Sentaurus device simulator package [18]. The model is based on a model developed in [19] and is applied at the source $p+/n$ (tunneling) junction in these simulations. The nonlocal tunneling model considers the entire potential path over which tunneling occurs in calculating the tunneling probabilities using the Wenzel–Kramers–Brillouin (WKB) approximation. Transport away from the tunnel junction is treated via drift–diffusion. Standard Shockley–Read–Hall recombination is turned on, and Fermi statistics are used. Dopant-induced bandgap narrowing is turned off. The simulations used the tunneling masses $m_c = 0.2 \times m_0$ and $m_v = 1.0 \times m_0$. The simulations performed to test the sensitivity to these parameters reveal that the reduced energy gap is the key determinant of the simulated tunneling current. Fig. 8 compares the measured and simulated transfer characteristics for devices with varying Ge content in the strained layer. Excellent agreement is achieved after adjusting for the energy gap of strained-SiGe layers by using $E_{\text{geff}}$ values of 0.7 and 0.6 eV for the 43%- and 57%-Ge-content devices, respectively, which are in close agreement with the independently extracted values from $C–V$ profiling. The SiGe devices also show large enhancements in the device current as compared to the silicon devices. Such enhancements are expected to occur (for the same biasing voltages) with reduction in $E_{\text{geff}}$ [7]. The good agreement in the shape and magnitudes of the characteristics between measurements and simulations using the tunneling model suggests that the current in the SiGe devices is BTBT dominated. The deviation between measurement and simulation for the Si control device suggests that the current is dominated by thermal generation mechanisms, such as trap-assisted leakage for $V_{gs} < 4.5$ V (a region of extremely low current). Previously [7], it was shown that the 0%-Ge-content devices (Si control) have a large temperature dependence on the gate-controlled characteristics as compared to the nearly insensitive characteristics of devices that had 40% Ge concentration. The “off-state” current ($I_{\text{off}}$) of these strained-SiGe devices is set by the intrinsic reverse-bias junction leakage, which increases (as expected) with reduced $E_{\text{geff}}$.

Device operation can be understood by examining the energy-band diagram. Fig. 9 shows the energy-band diagrams in the OFF and ON states for the 43%-Ge-content device. Increased $V_{gs}$ reduces the required tunneling distance, thus enabling BTBT to occur and overtake the intrinsic junction leakage of strained-SiGe devices.

Fig. 8. Measured and simulated transfer characteristics (using a nonlocal BTBT model with WKB approximation) for varying Ge content. Excellent agreement is achieved using $E_{\text{geff}}$ values consistent with the $C–V$ extractions (Fig. 3). BTBT is dominant in the 57%-Ge-content device, while trap-assisted leakage dominates the Si device.

Fig. 9. Energy-band diagram in the OFF and ON states for the 43%-Ge-content device. Increased $V_{gs}$ reduces the required tunneling distance, thus enabling BTBT to occur and overtake the intrinsic junction leakage of strained-SiGe devices.
in dose as an increase in the doping concentration of the p+ source and keeping the gradient of the doping profile constant (~45 nm/decade). The tunneling simulations also predict a slow turn-on with $V_{ds}$ and a saturation of the drain current with $V_{ds}$, which are in agreement with the measurements. Fig. 11 also shows the simulated 2-D electron-current-density contours in the 43%-Ge-content device at various values of $V_{ds}$. Increased $V_{ds}$ causes increased depletion of the n-type surface and eventual disconnection of the drain potential to the tunneling region thus leading to saturation of the drain current with $V_{ds}$. Similar behavior has been predicted to occur in TFET devices, as shown in [20]. The gentle turn-on with $V_{ds}$ observed in TFET devices (i.e., the high ON-resistance at zero $V_{ds}$) is a concern for circuit design. The measurements of the test structures in this paper, however, show that routes for improving this turn-on are potentially possible with sharpening of the doping profile, using a thinner EOT and even a more reduced $E_{geff}$.

In [8], a potentially improved device structure that utilizes a p+ strained-Ge/strained-Si type-II staggered energy-band offset as the source (tunnel junction) of a TFET device has been proposed (LHTFET). Fig. 12 shows the extracted local SS versus $I_d$ for all measured strained-SiGe devices (shown in this paper) and the simulated projections for potentially improved structures, such as the LHTFET, which is discussed in more detail in [8]. Simulations that are consistent with the measured behavior of devices in this paper indicate that LHTFETs may achieve a sub-60-mV/dec $I_d$-versus-$V_{gs}$ swing over more than four orders of magnitude in $I_d$ while maintaining large drive currents at $V_{ds}=0.4$ V.

V. SUMMARY

In summary, measurements and simulations have been used to quantify the physics of strained-Si$_{1-x}$Ge$_x$/Si gated diodes operating as TFETs. The improvement in the switching char-
acteristics with increased Ge content and doping concentration was observed experimentally and is in good agreement with the simulations using a nonlocal tunneling model. It was experimentally demonstrated that a strained-SiGe bandgap of 0.55 eV resulted in an increase in ON-current by 10\(^3\), relative to Si control devices, and it is expected that further increases in Ge content and doping concentration will dramatically improve the switching characteristics of TFETs.

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REFERENCES


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