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and Doping Concentration on Switching Behavior*

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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

Osama M. Nayfeh, *Member, IEEE*, Judy L. Hoyt, *Fellow, IEEE*, and Dimitri A. Antoniadis, *Fellow, IEEE*

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 10¹⁹–10²⁰ 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_{geff}) 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_{ds}). Simulations are also performed to project the potential performance of more optimized structures that may be suitable for extremely low power applications ($V_{\text{dd}} < 0.4$ 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 large- $I_{\text{on}}/I_{\text{off}}$ 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 10¹⁹–10²⁰ 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_{geff}) 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_{ds}). 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 $\mu\text{A}/\mu\text{m}$ 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- $\Omega \cdot \text{cm}$) wafers. A 2- μm -thick Si layer was first grown, with *in situ* PH₃ doping, to a level of 10¹⁷ cm⁻³. The strained-Si_{1-x}Ge_x (0%, 43%,

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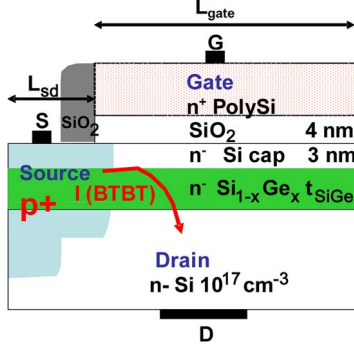


Fig. 1. Device schematic: $L_{\text{gate}} = 50 \mu\text{m}$ and $W = 10 \mu\text{m}$. The source dimensions are $L_{\text{sd}} = 6 \mu\text{m} \times W_{\text{sd}} = 10 \mu\text{m}$. When operated as a TFET, the n-type substrate serves as the drain, collecting the carriers generated by gate-induced BTBT.

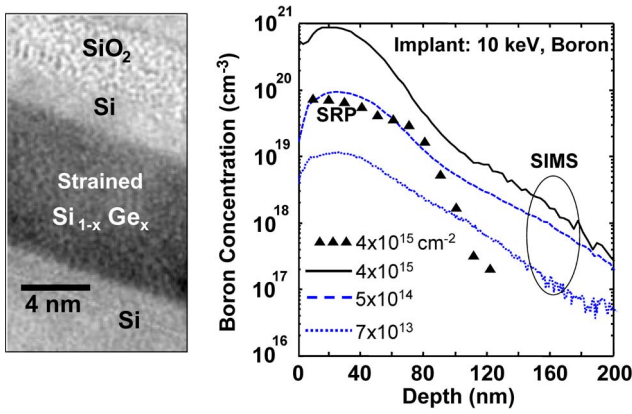


Fig. 2. (Left) XTEM of the fabricated strained-Si_{0.57}Ge_{0.43} device in the channel region. (Right) SIMS and SRP data of the p⁺ source for various B implant doses. The highest dose implant achieved an active doping concentration of $\sim 10^{20} \text{ cm}^{-3}$ (limited by the 800-°C 10-s RTA).

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} cm^{-3} . After MOSFET processing, the final structure had an unstrained-Si cap thickness of 3 nm, a gate SiO₂ thickness of 4 nm, and an n⁺ *in situ* doped polysilicon gate. The gate oxide was grown at 600 °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 (7×10^{13} – $5 \times 10^{14} \text{ cm}^{-2}$). Ion implants were activated by rapid thermal annealing at 800 °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_{1-x}Ge_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

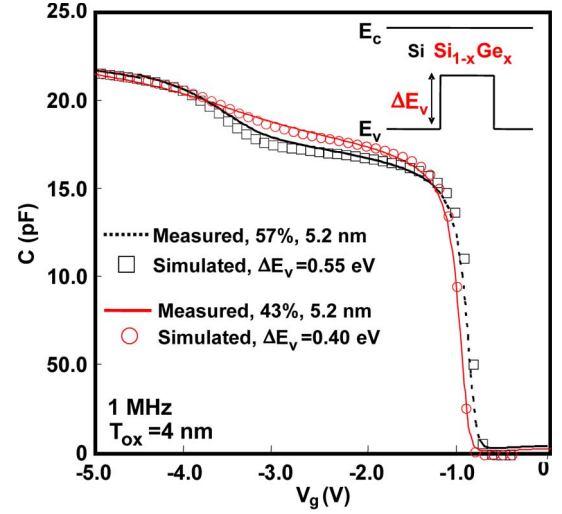


Fig. 3. Measured ($50 \mu\text{m} \times 50 \mu\text{m}$) and simulated C - V profiles for devices with 43% and 57% Ge contents. The extracted valence-band offsets ΔE_v 's are 0.4 and 0.55 eV, respectively, corresponding to energy-gap values of 0.7 and 0.55 eV, which are much reduced compared to Si.

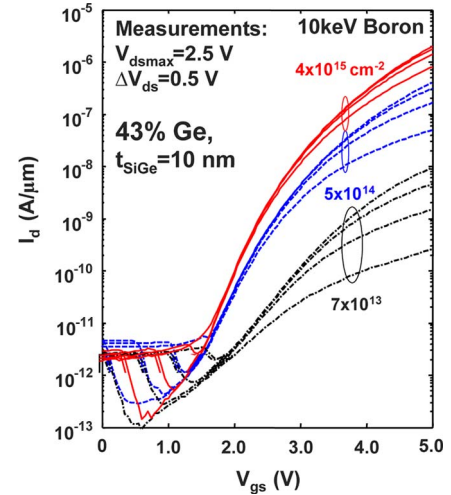


Fig. 4. Measured transfer characteristics for 43%-Ge-content devices with varying B implant dose. Increased dose increases the current drive of the devices and improves the SS. $L_{\text{gate}} = 50 \mu\text{m}$ and $W = 10 \mu\text{m}$.

fitting C - V profiles [12], [13] (Fig. 3), valence-band offsets (ΔE_v 's) of 0.4 and 0.55 eV are extracted for the 43%- and 57%-Ge-content devices, corresponding to effective energy barrier values for tunneling (E_{geff}) of 0.7 and 0.55 eV, respectively. Such reductions in E_{geff} due to a large valence-band offset between strained SiGe and silicon are consistent with other works that determined valence-band offsets [12]–[17]. We note that the extraction procedure could produce errors of $\pm 0.1 \text{ eV}$ due to assumptions and uncertainties.

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. Fig. 5 shows the measured output characteristics of 43%-Ge-concentration devices with varying 10-keV implant dose.

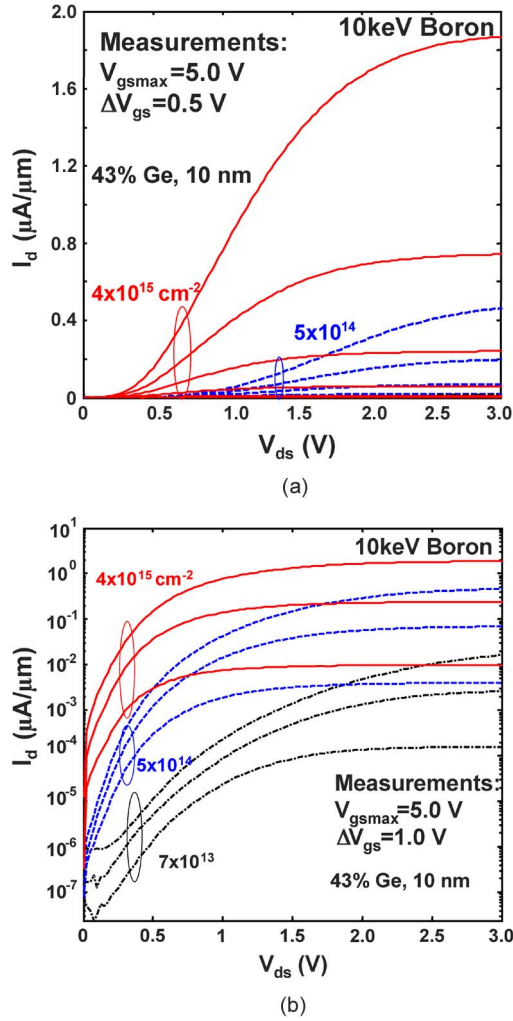


Fig. 5. Measured TFET output characteristics on (top) linear and (bottom) log scales for 43%-Ge-content devices with varying implant dose (10-keV boron). The devices exhibit a slow turn-on as a function of V_{ds} and saturation with V_{ds} (in agreement with theory [20]). Increased implant dose (junction doping) improves the turn-on behavior in both the turn-on threshold and the sharpness of turn-on. $L_{gate} = 50 \mu\text{m}$ and $W = 10 \mu\text{m}$.

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 $8 \mu\text{A}/\mu\text{m}$, 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

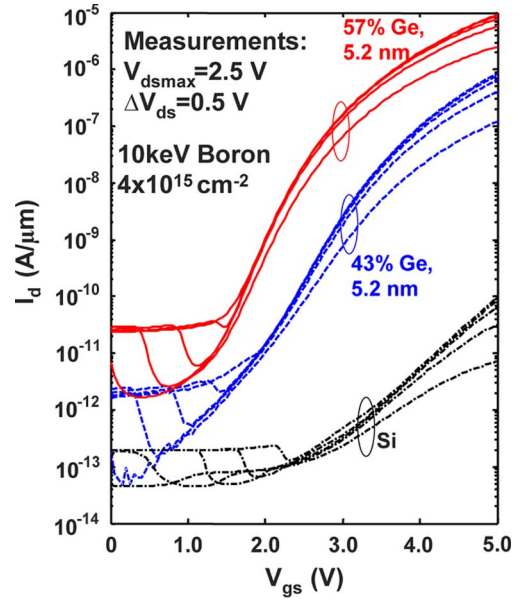


Fig. 6. Measured transfer characteristics for devices with varying Ge content (0%, 43%, and 57% Ge). Increased Ge content increases the current drive due to reduction of the energy barrier for tunneling (E_{geff}). $L_{gate} = 50 \mu\text{m}$ and $W = 10 \mu\text{m}$.

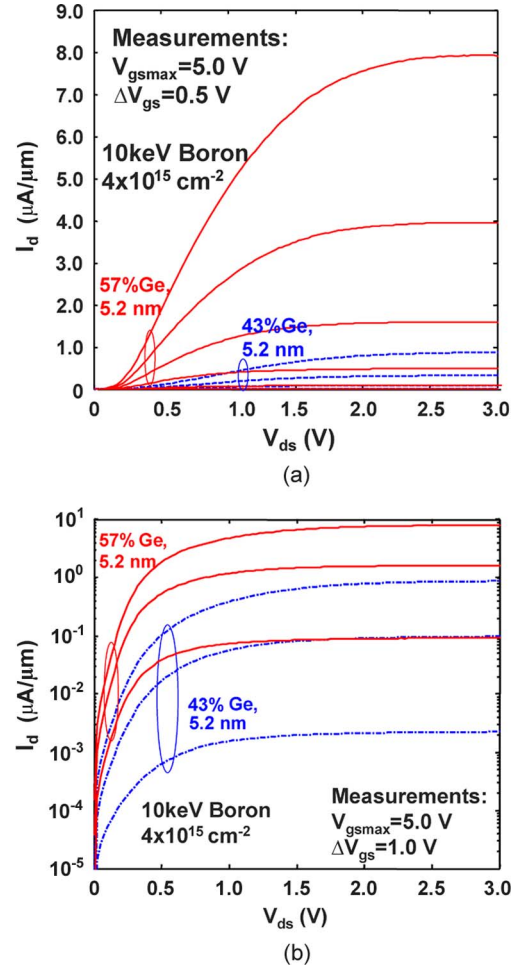


Fig. 7. Measured output characteristics on (top) linear and (bottom) log scales for devices with varying Ge content (43% and 57% Ge). Increased Ge content further improves the turn-on behavior as a function of V_{ds} (reduced turn-on threshold and increased sharpness of turn on). $L_{gate} = 50 \mu\text{m}$ and $W = 10 \mu\text{m}$.

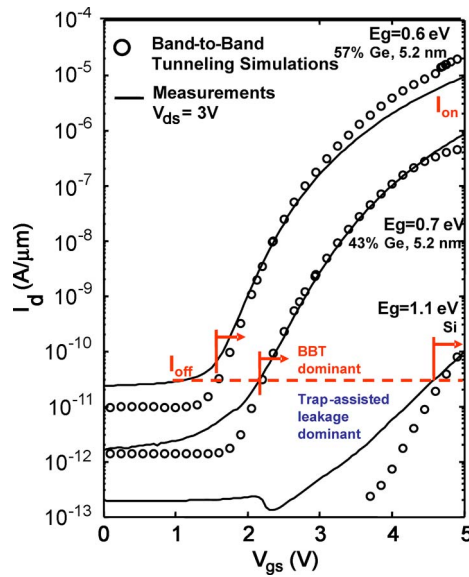


Fig. 8. Measured and simulated transfer characteristics (using a nonlocal BTBT model with WKB approximation) for varying Ge content. Excellent agreement is achieved using E_g values consistent with the C - V extractions (Fig. 3). BTBT is dominant in the 57%-Ge-content device, while trap-assisted leakage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

expected with reduction in gate-dielectric EOT, sharper doping profiles, and further reduction in E_{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 doping profiles of the p+/n junctions are approximated via TSUPREM simulations with input from the SIMS measurement analysis. Simulations were performed using the tunneling masses $m_c = 0.2 * m_0$ and $m_v = 1.0 * m_0$. 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_{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_{geff} [7]. The good agreement in the shape and magnitudes of the characteristics between measurements and

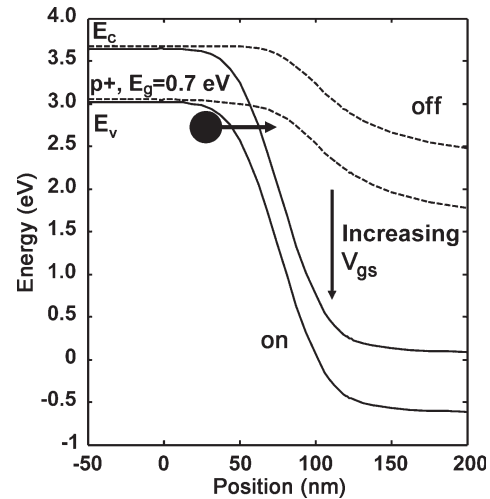


Fig. 9. Energy-band diagram in the OFF and ON states for the 43%-Ge-content device. Increased V_{gs} reduces the required tunneling distance, thus enabling BTBT to occur and overtake the intrinsic junction leakage of strained-SiGe devices.

simulations using the tunneling model suggests that the current in the SiGe devices are 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_{off}) of these strained-SiGe devices is set by the intrinsic reverse-bias junction leakage, which increases (as expected) with reduced E_{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 tunnel distance, enabling the BTBT current to overtake the intrinsic junction leakage. Continued increases of V_{gs} result in further reduction of the tunnel distance and, hence, larger device drive current. In these devices, there is gradual change of the tunneling distance with V_{gs} modulation because the source doping gradient is relaxed (~ 45 nm/dec) and the EOT is relatively thick (4 nm), which thus limits the minimum SS [8]. Interface trap density does not appear to impact the SS as the MOSFET results show that the Si cap was not breached by Ge diffusion and that D_{it} levels are low. Fig. 10 shows the simulated 2-D BTBT carrier generation rates in the 43%-Ge-content device in the ON state. Electrons leave the valence band (generation of holes) of the p+ source via tunneling to the conduction band (generation of electrons) of the accumulated channel in a nonlocal process in the Si_{1-x}Ge_x layer. Fig. 11 compares the measured and simulated output characteristics demonstrating good agreement in the shape of the characteristics, as well as improvement in the switching behavior with increasing Ge content and source doping. Good agreement between measurements and simulations of the output characteristics is achieved by approximating the increase

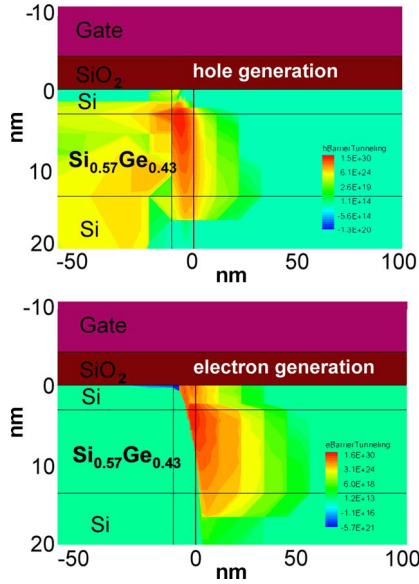


Fig. 10. Simulated 2-D BTBT hole/electron generation rates (in per cubic centimeter per second) in the 43%-Ge-content device in the ON state. Electrons tunnel from the valence band (generation of holes) to the conduction band (generation of electrons) in a nonlocal process in the reduced E_g layer.

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_{dd} of 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-

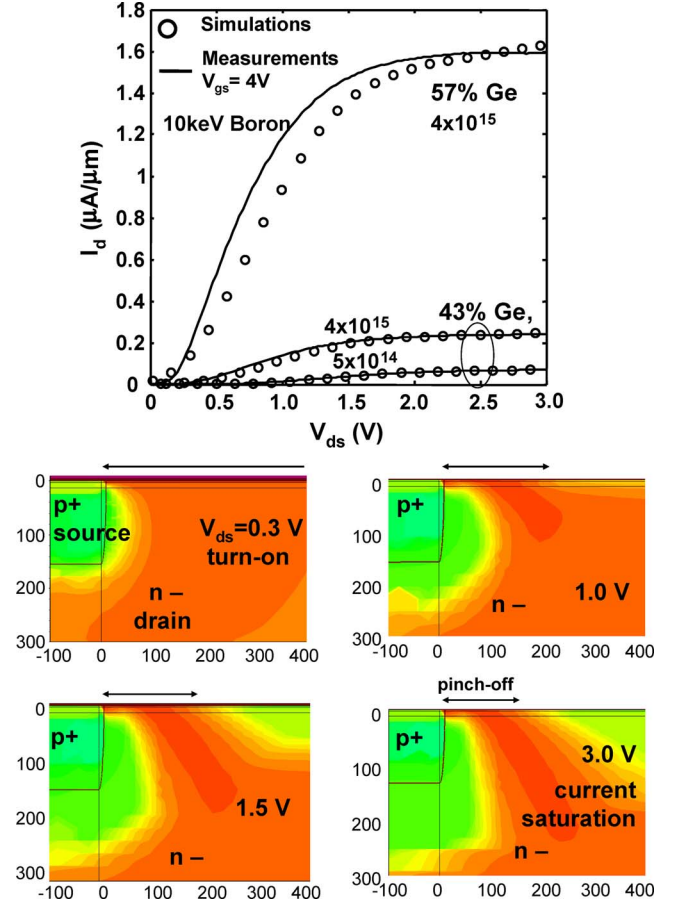


Fig. 11. (Top) Measured and simulated output characteristics with varying Ge concentration and junction dose. Simulations using the QM BTBT model produce good agreement with the shape of the measured characteristics. The 57%-Ge-content device required a scale factor of 0.7 to the simulated current to produce good agreement with the current magnitude at V_{gs} of 4 V. (Bottom) Simulated 2-D electron-current-density contours in the 43%-Ge-content device at various values of V_{ds} . With increasing V_{ds} , the n-type surface begins to deplete, so the current profiles are brought in toward the source, until, eventually (at saturation), the drain potential is disconnected from the edge of the channel due to the onset of weak inversion and/or depletion there.

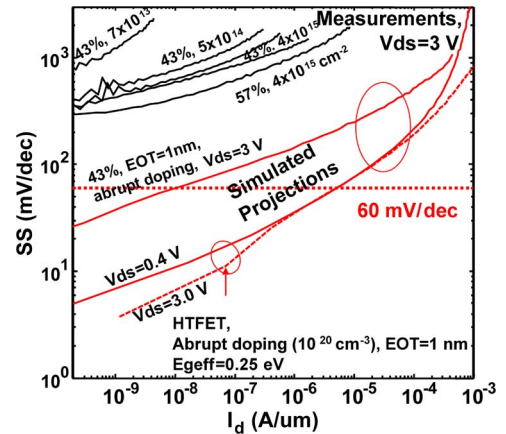


Fig. 12. Local SS for the measured devices and for the simulated projections of the improved devices (sharper doping, reduced EOT, and reduced energy barrier for tunneling, e.g., the strained-Si/strained-Ge LHTFET) [8]. The measured devices have a minimum $SS_{min} \sim 300$ mV/dec due to relaxed junction doping and thick EOT. Simulations suggest that LHTFETs [8] may achieve sub-60 mV/dec over a wide I_d range.

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 10^5 , 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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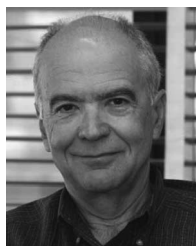
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