Theoretical Insights and Modeling of Vertical GaN Switches for Industrial Applications

Samaneh Sharbati, Associate professor,
University of Southern Denmark

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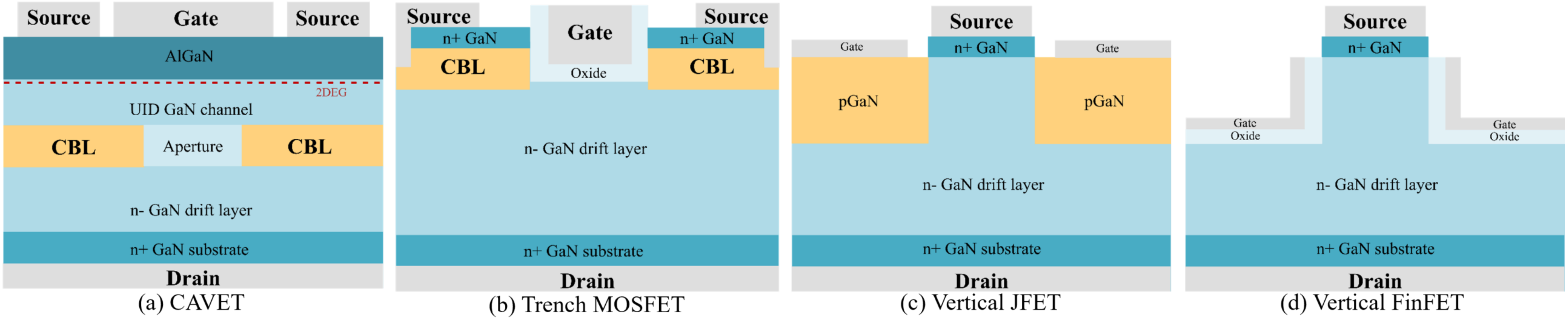
Event 2024

Making WBG Designs Happen

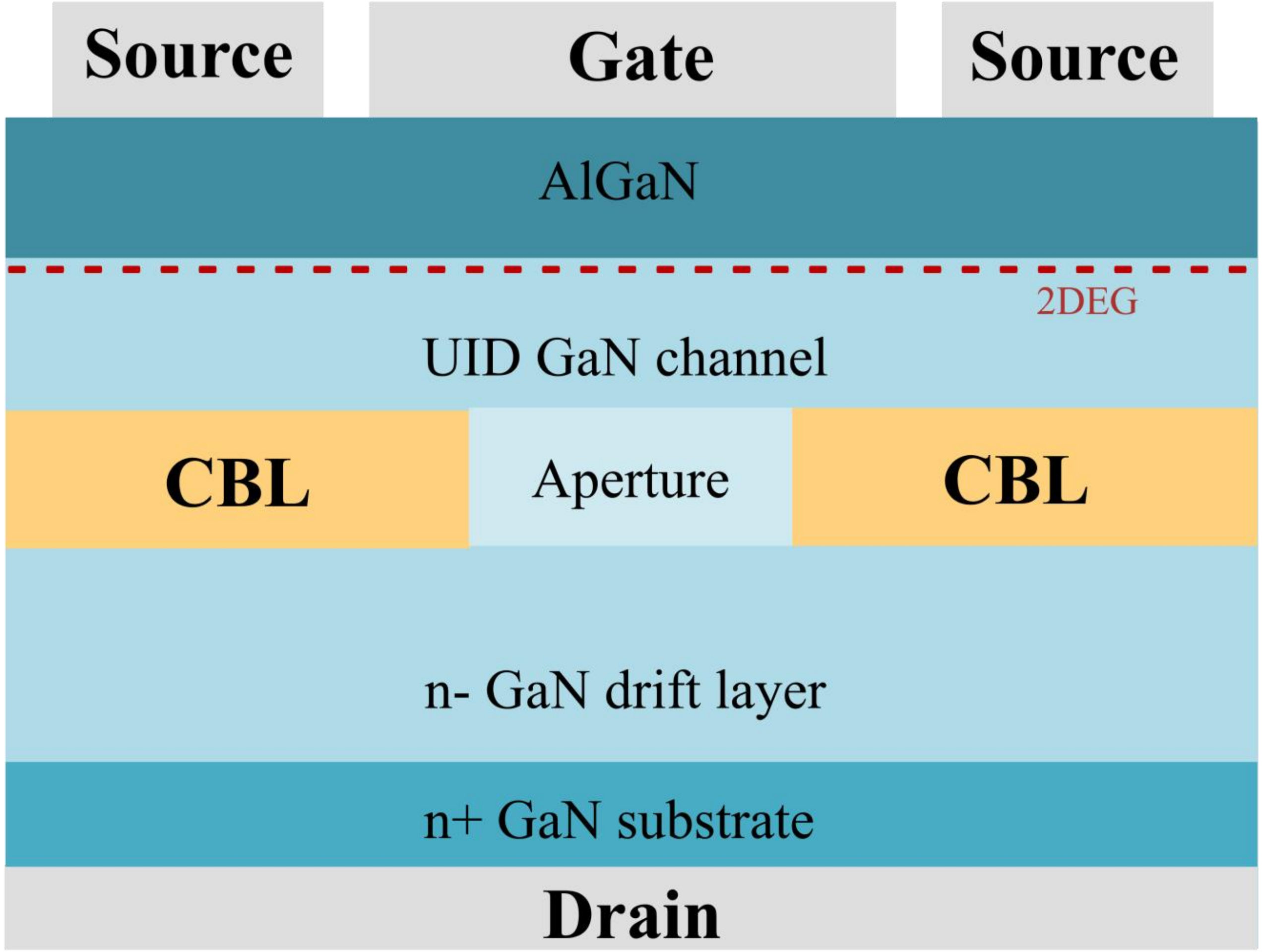
GaN

Vertical GaN Transistors



GaN-based vertical transistors: (a) CAVET, (b) Trench MOSFET, (c) Fin FET and (d) JFET

CAVET : Current Aperture Vertical Electron

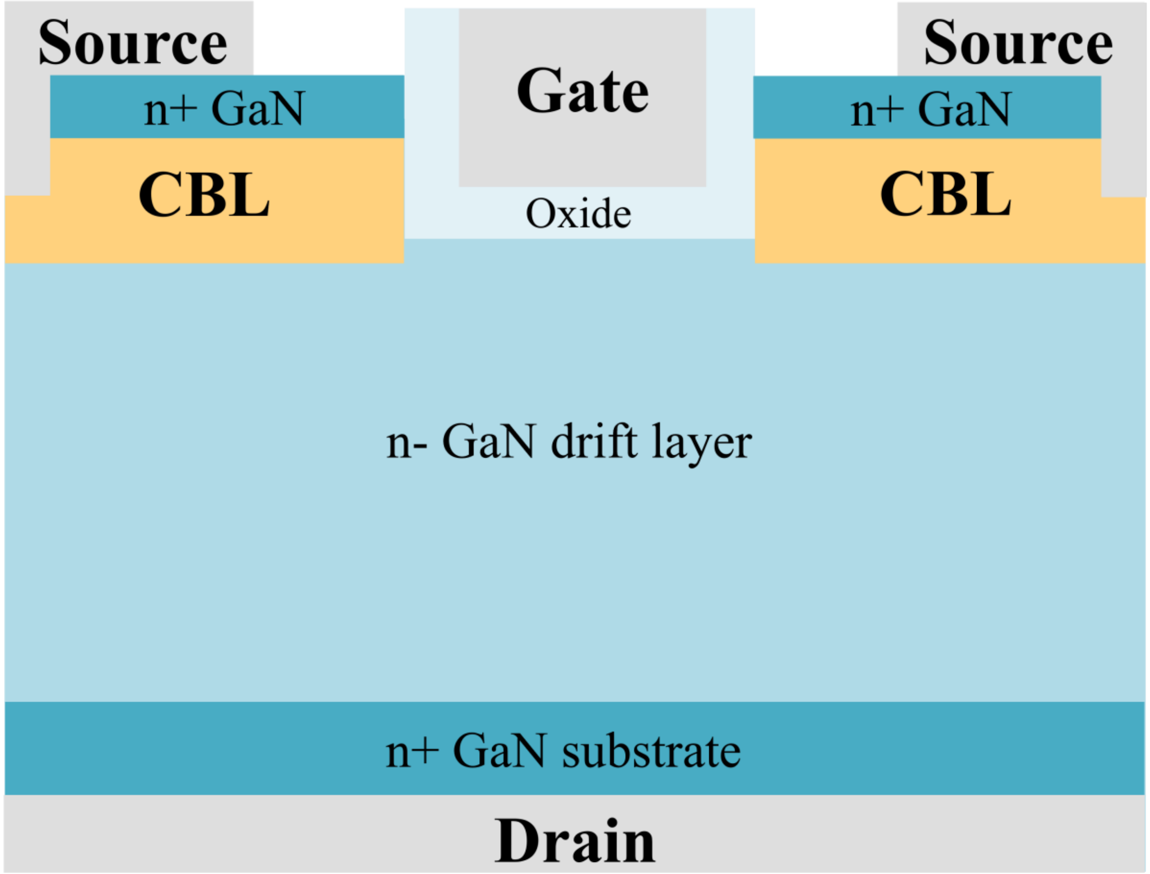


Conventional CAVET Structure

- Advantages
  - High channel conductivity due to 2DEG
  - High Breakdown Voltage
  - Reduced DC-RF Dispersion
  - Efficient Die Area Utilization

- Challenges
  - Leakage Paths
  - Device Design
  - Fabrication Technique
  - Achieving Normally-Off Operation

Vertical Trench MOSFET



Trench MOSFET cross sectional schematic

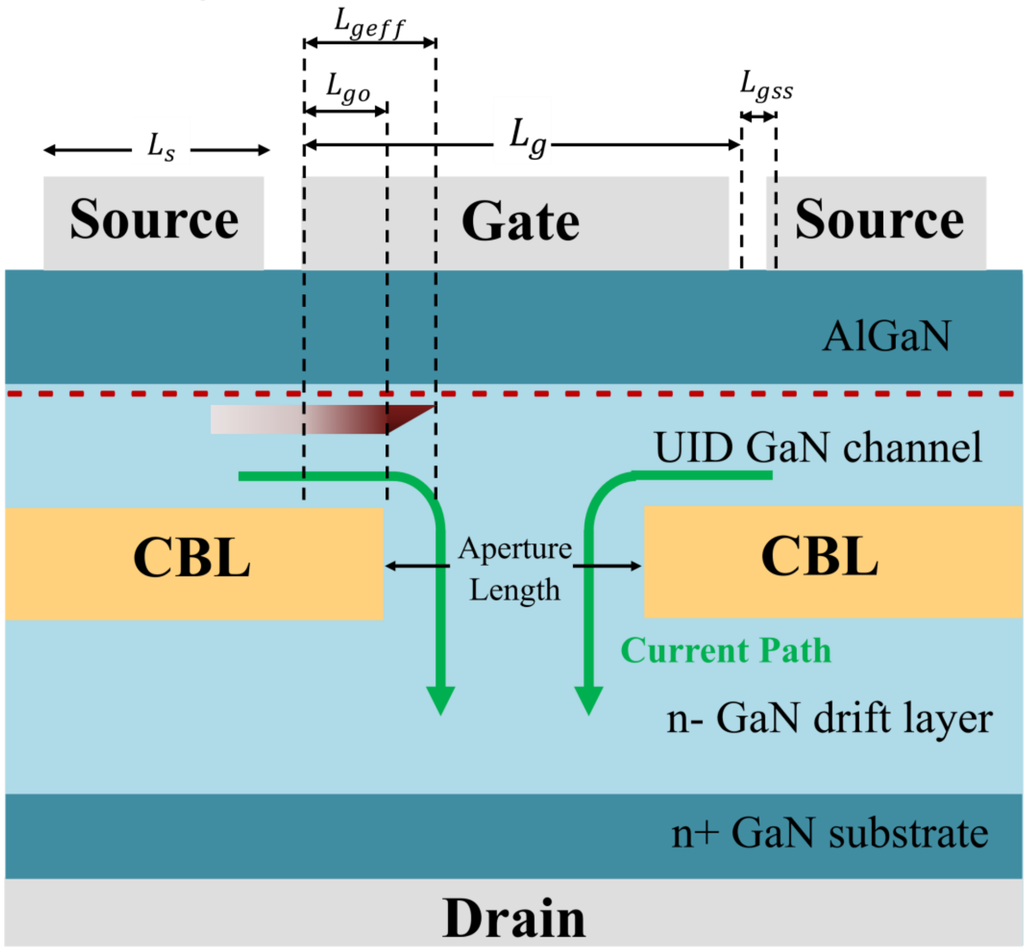
➢Advantages
- Normally off

➢Challenges
- Doesn’t utilize a 2DEG channel
- Low electron mobility
- Potential trapping effects
- Buried p-GaN Layer Activation
- Potential punch-through breakdown issues
- Very high turn on voltage.

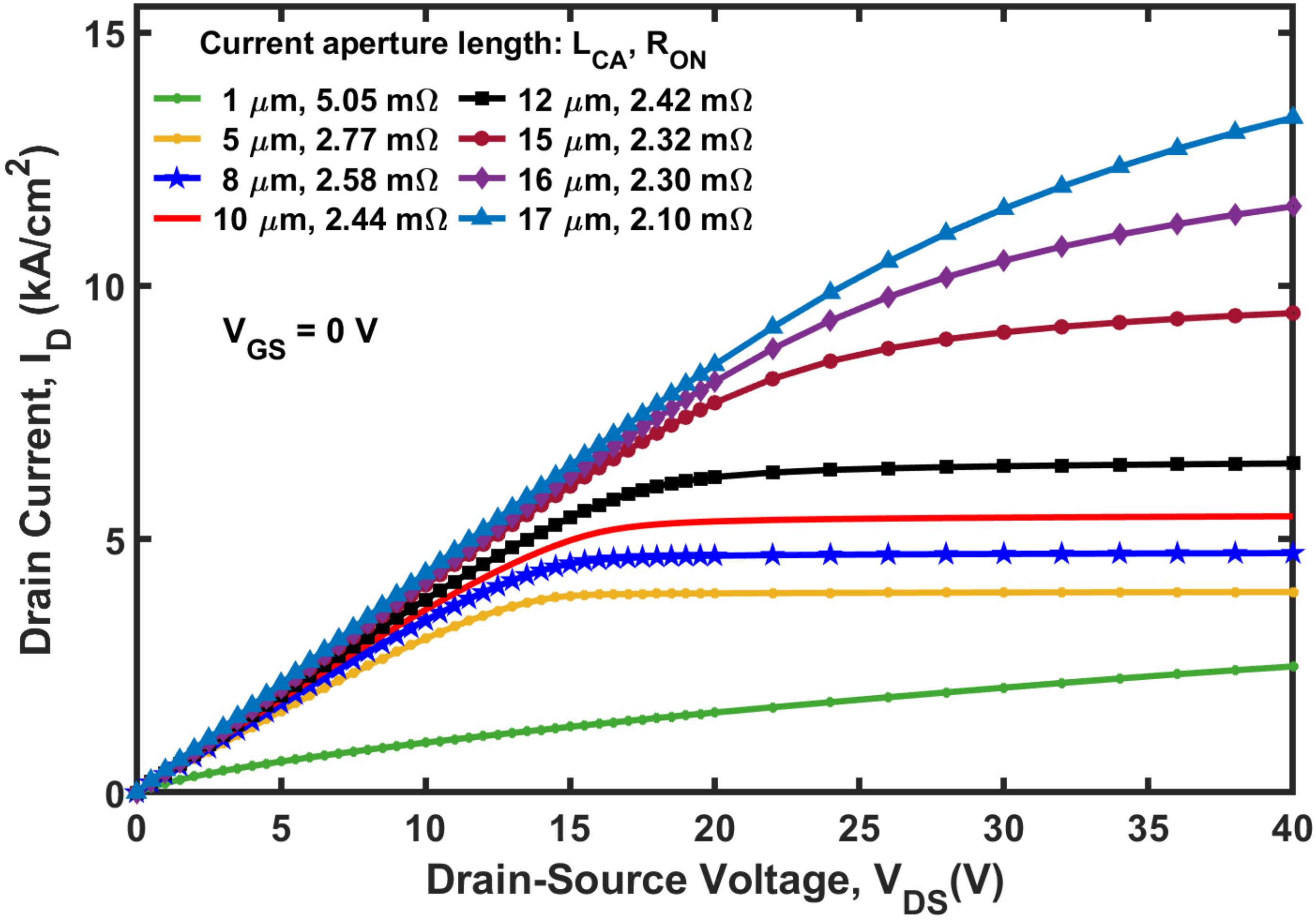
➢Application
- High power applications

Output Characteristics

- On-resistance decreases with the increase of the current aperture length.



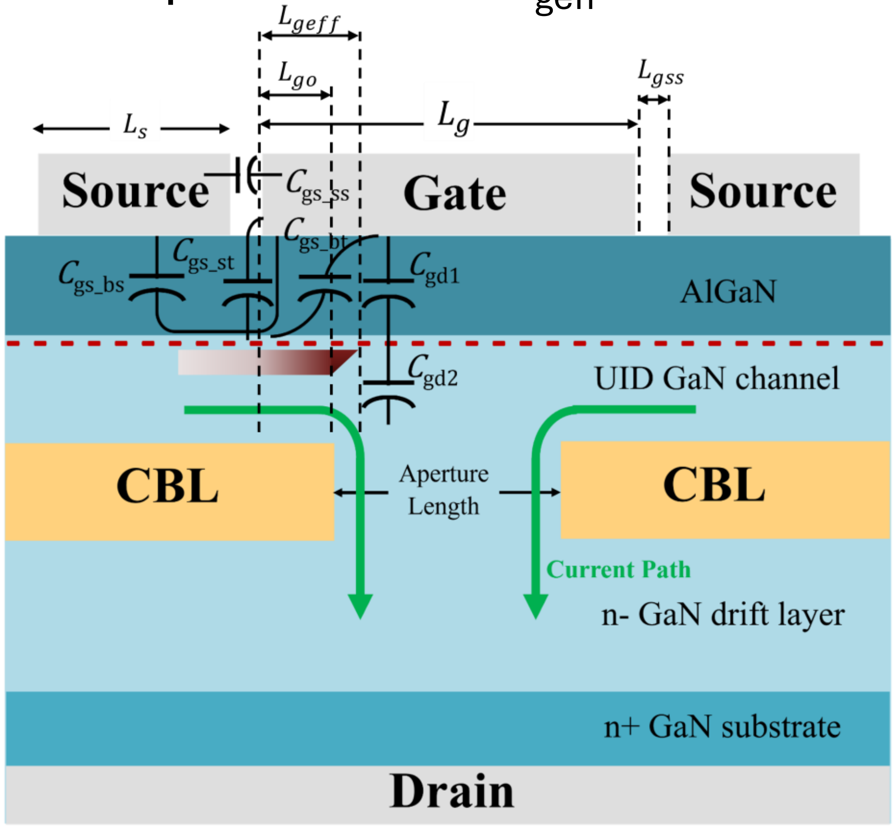
Conventional CAVET Structure



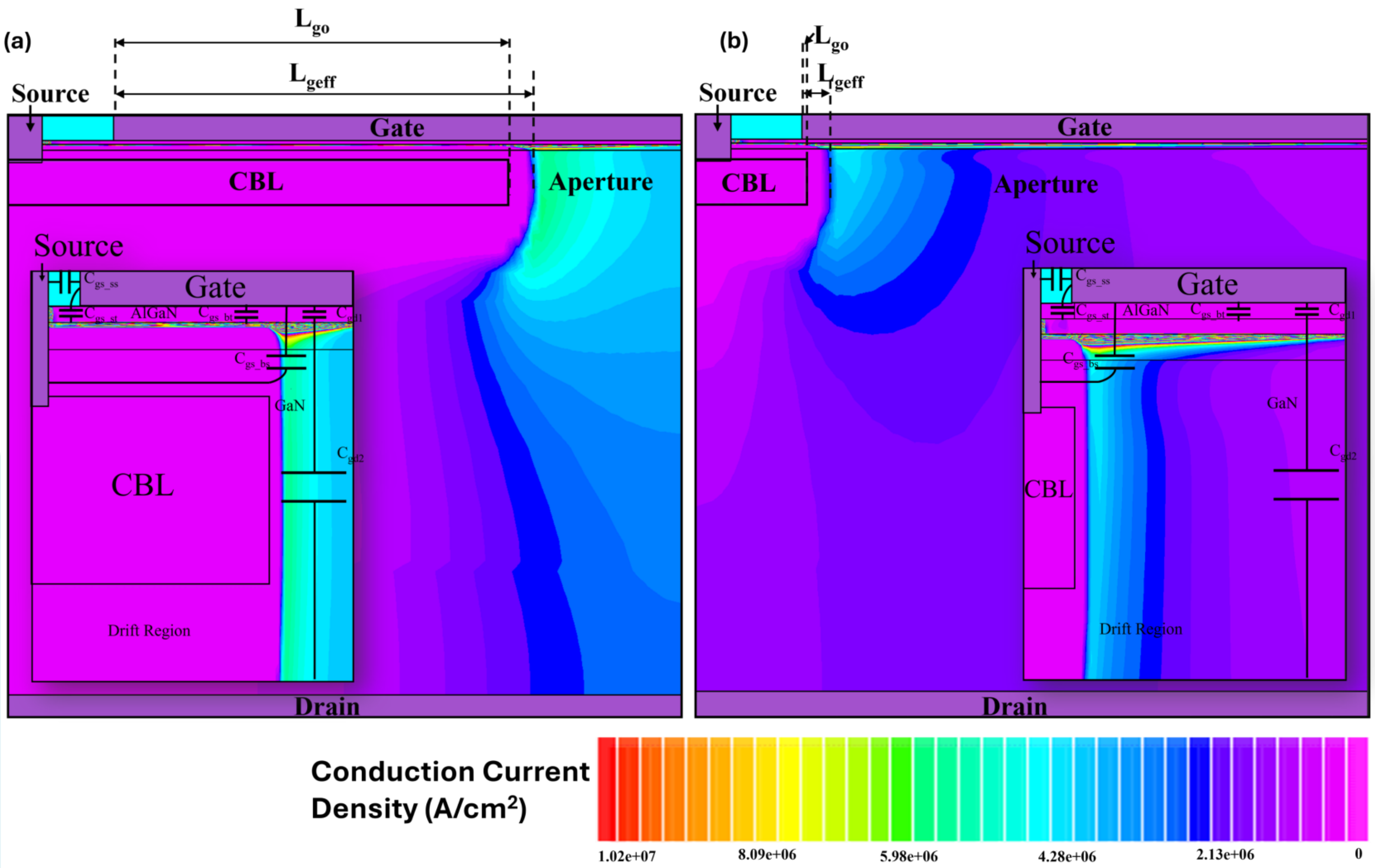
The output characteristics for different aperture lengths at V_{GS} = 0 V

Intrinsic Gate Capacitance

- The aperture length change the effective gate length (L_{geff})
- Intrinsic gate capacitance depends on the L_{geff}



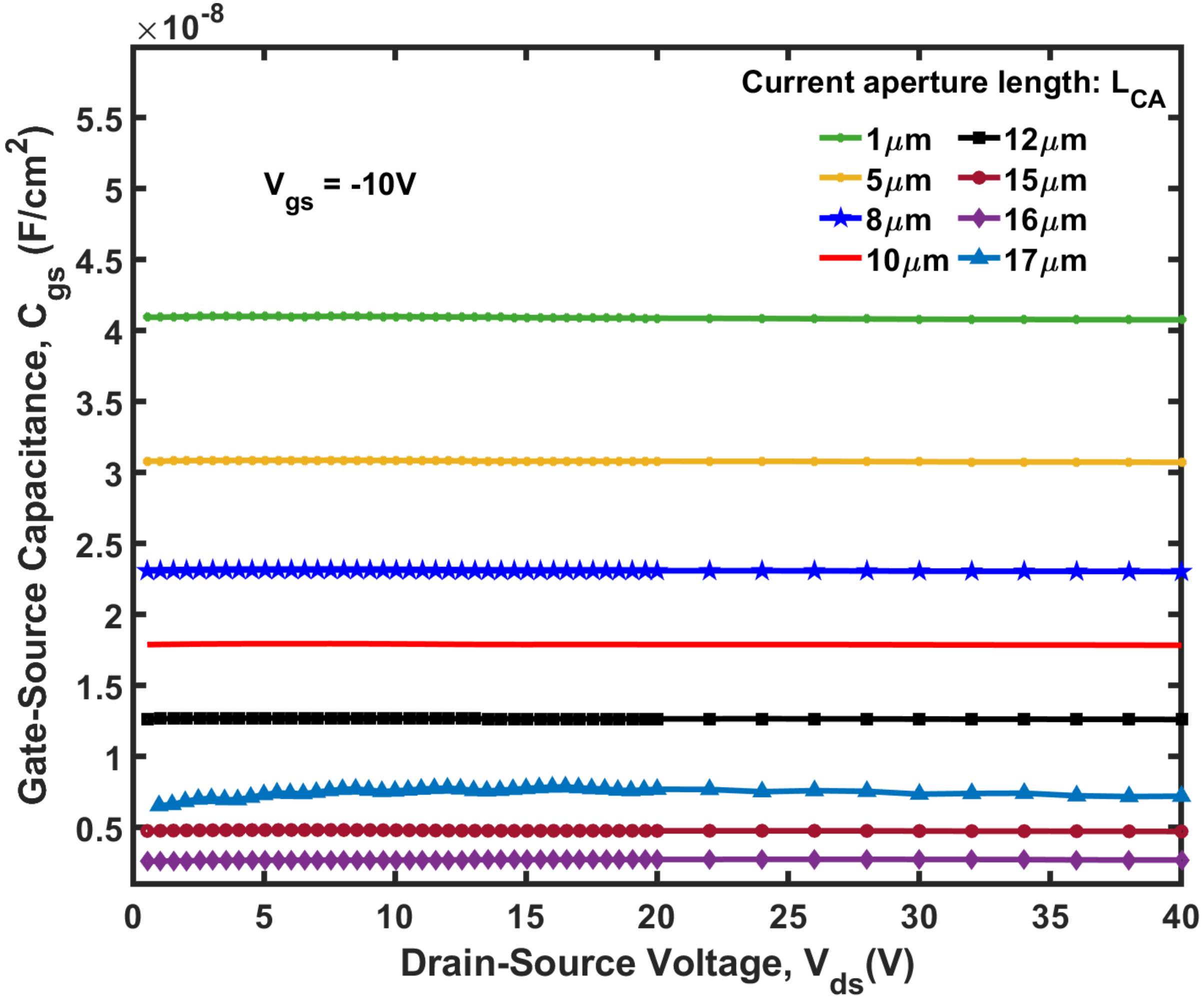
CAVET structure schematic with a simplified model of intrinsic gate capacitances



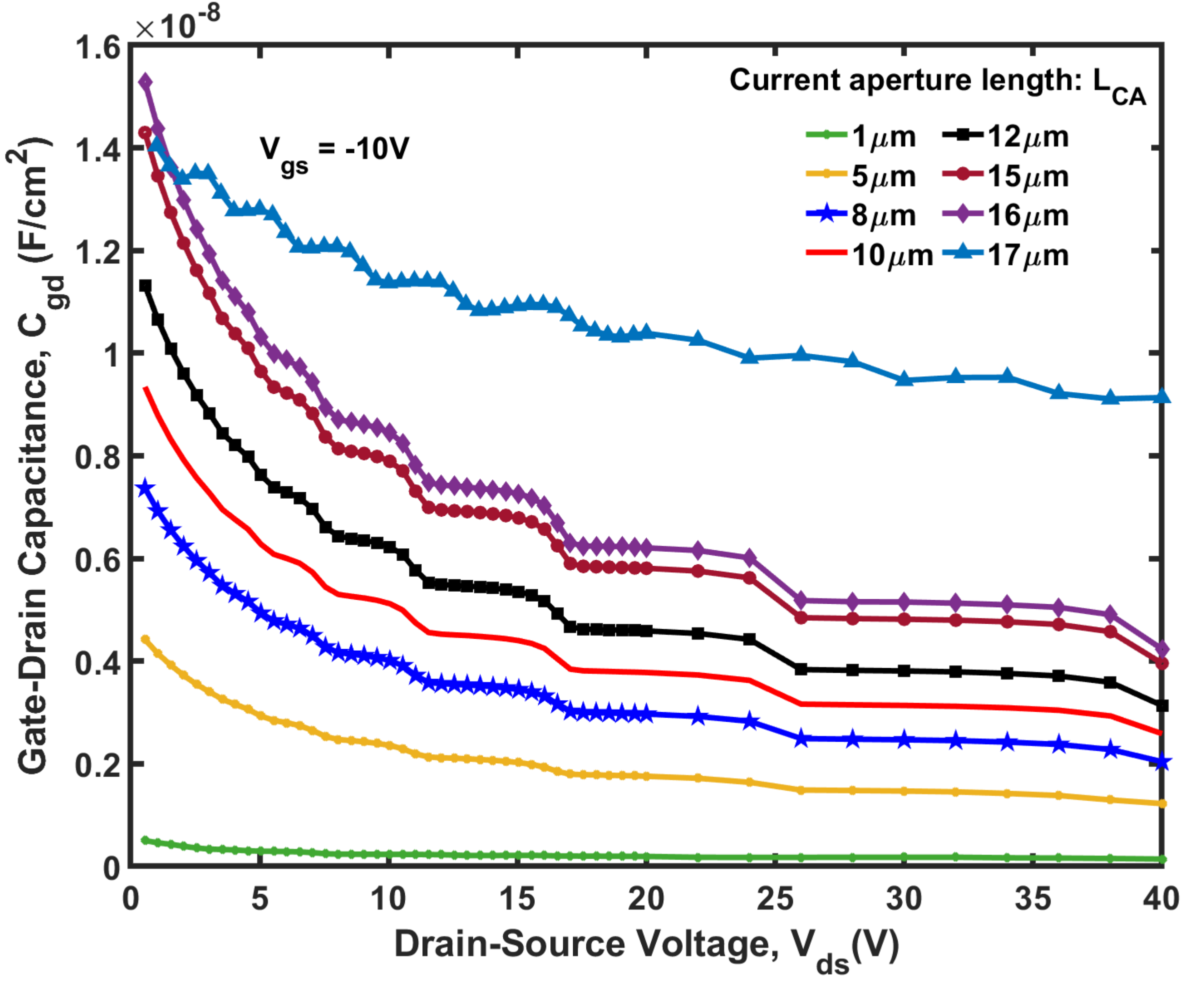
The conduction current density electron concentration of the CAVET structure with aperture lengths of (a) 5 μm, and (b) 16 μm.

CV characteristics

- Gate-Source Capacitance decreases with aperture length



Gate-source Capacitance

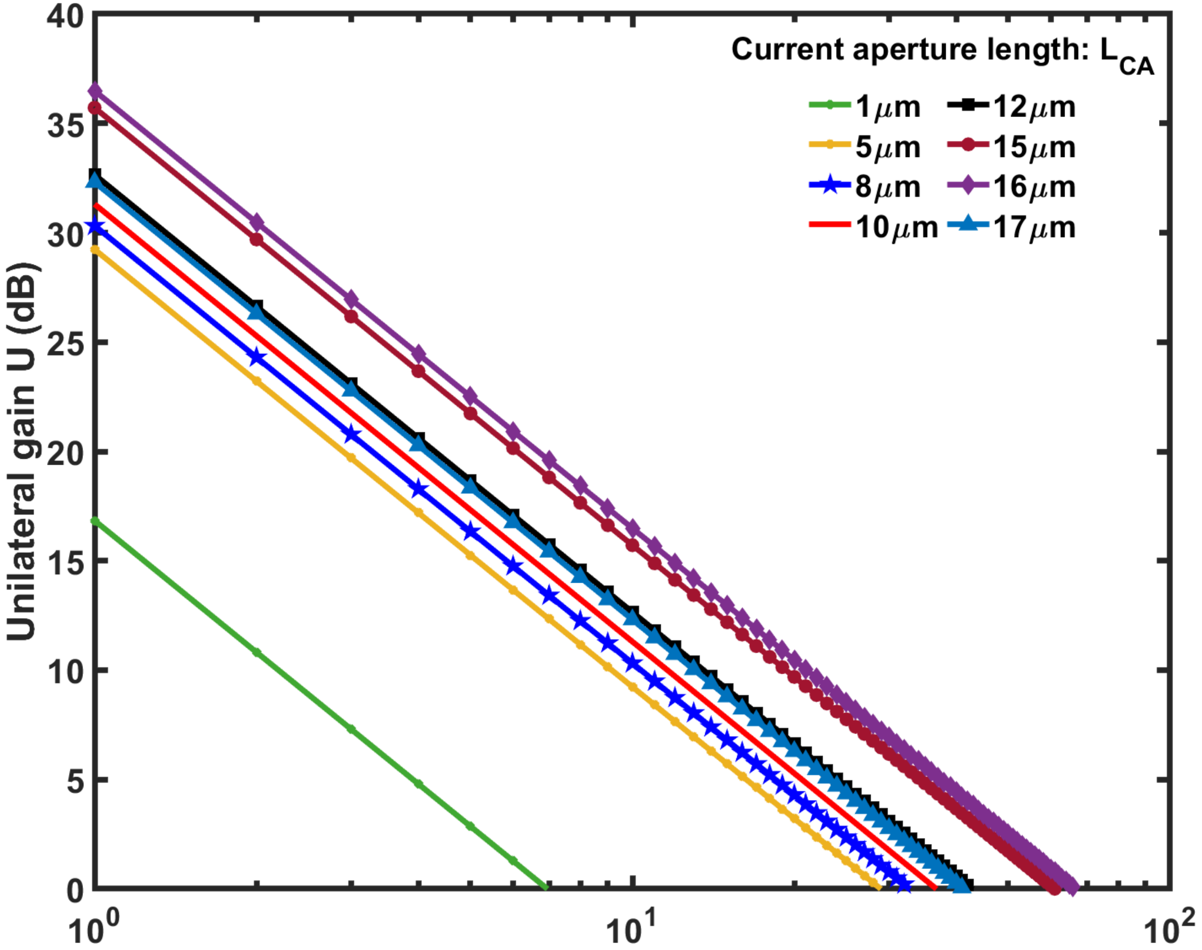


Gate-drain Capacitance

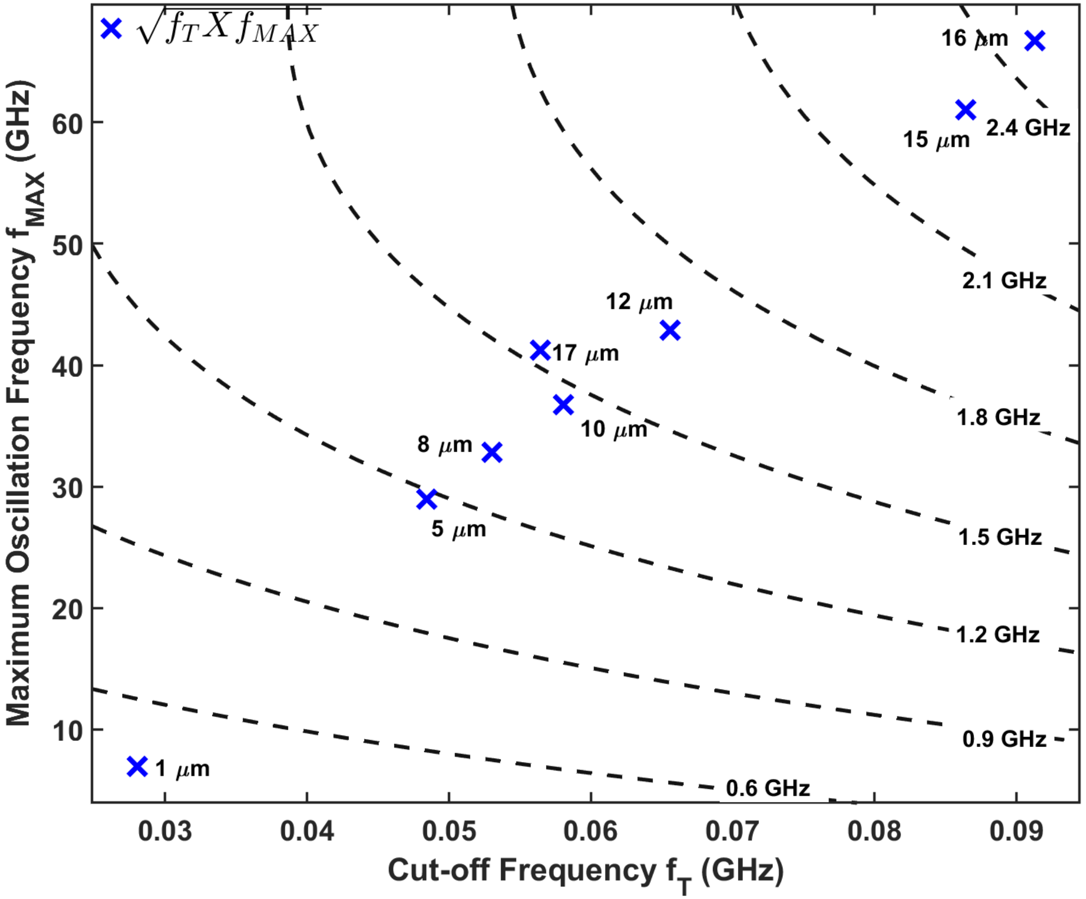
- Gate-drain Capacitance increases with aperture length

RF characteristics

- The unilateral power gain increases with the aperture length.



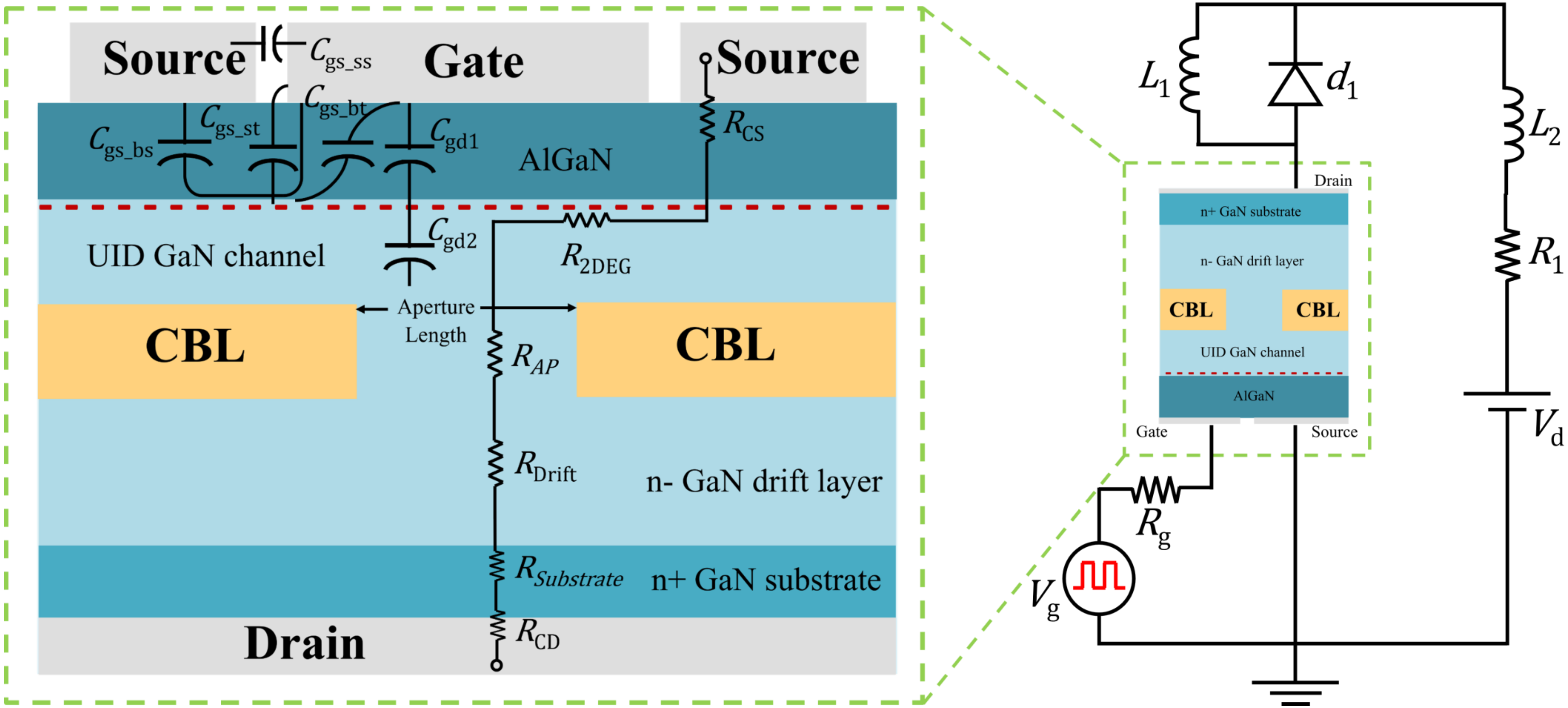
Mason's unilateral power gain (U) versus frequency



f_{MAX} against f_T for various aperture lengths of the CAVET

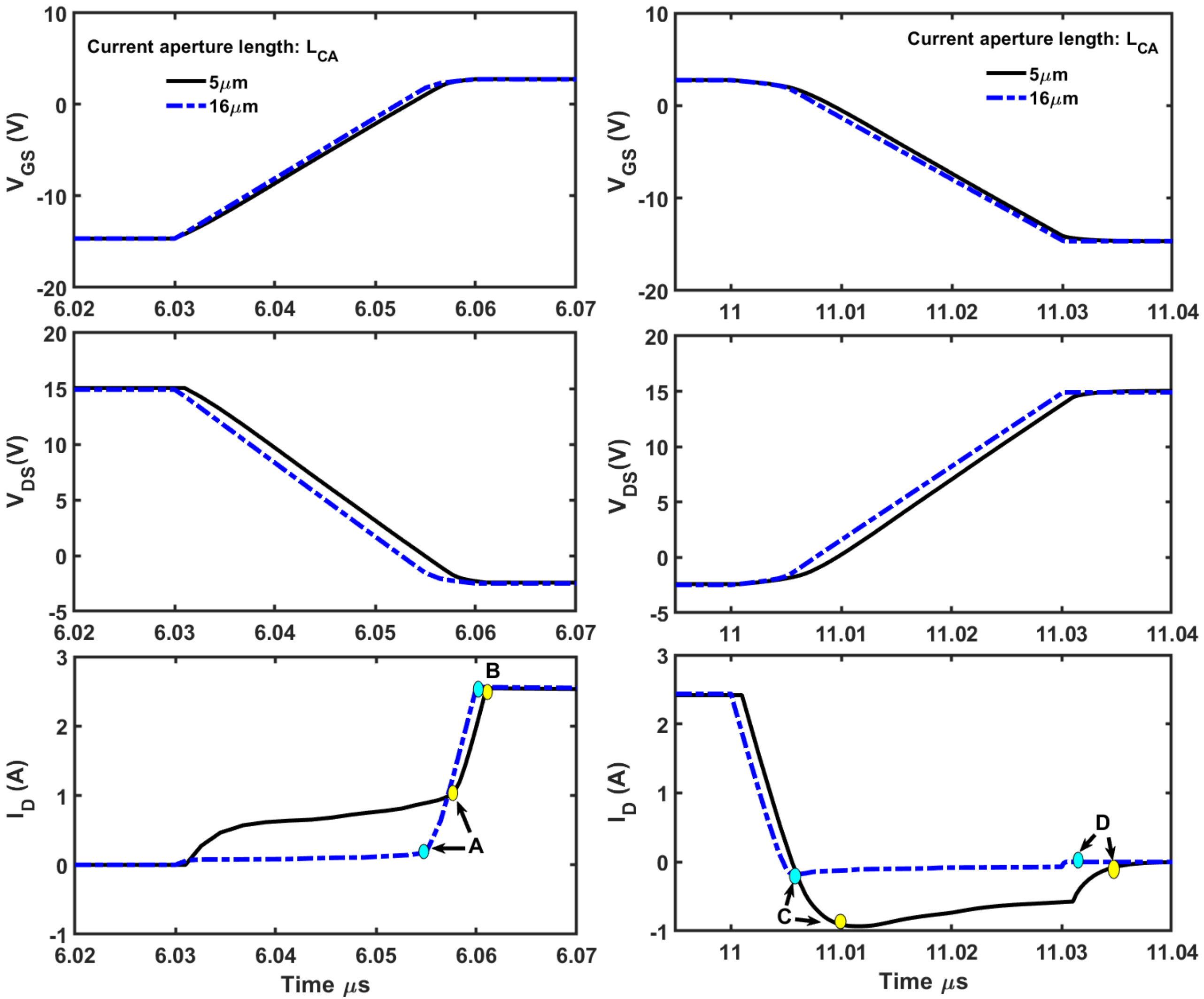
- The value of $\sqrt{f_T \times f_{Max}}$ for large aperture length is higher than 2.4 GHz.
- The peak values of f_T and f_{MAX} are 0.09 GHz and 66.73 GHz, respectively, achieved at L_{CA} = 16 μm.

Switching Circuit



Switching test circuit using CAVET

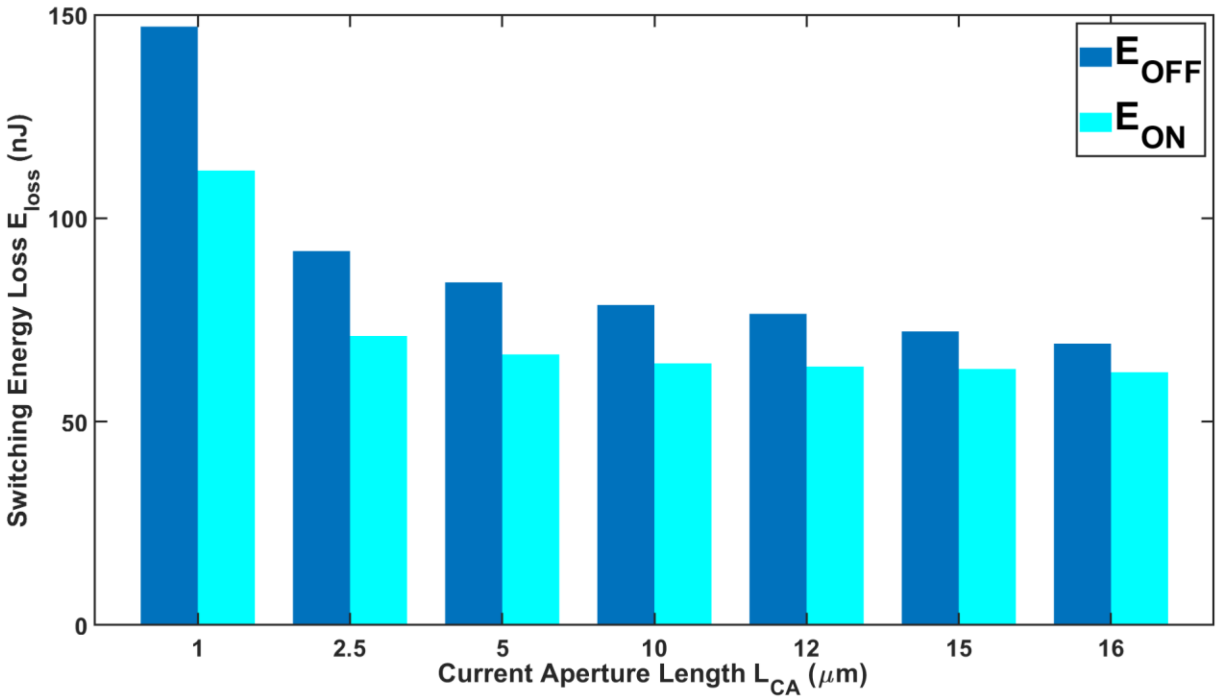
Switching Waveforms and Energy loss



(a) (b)

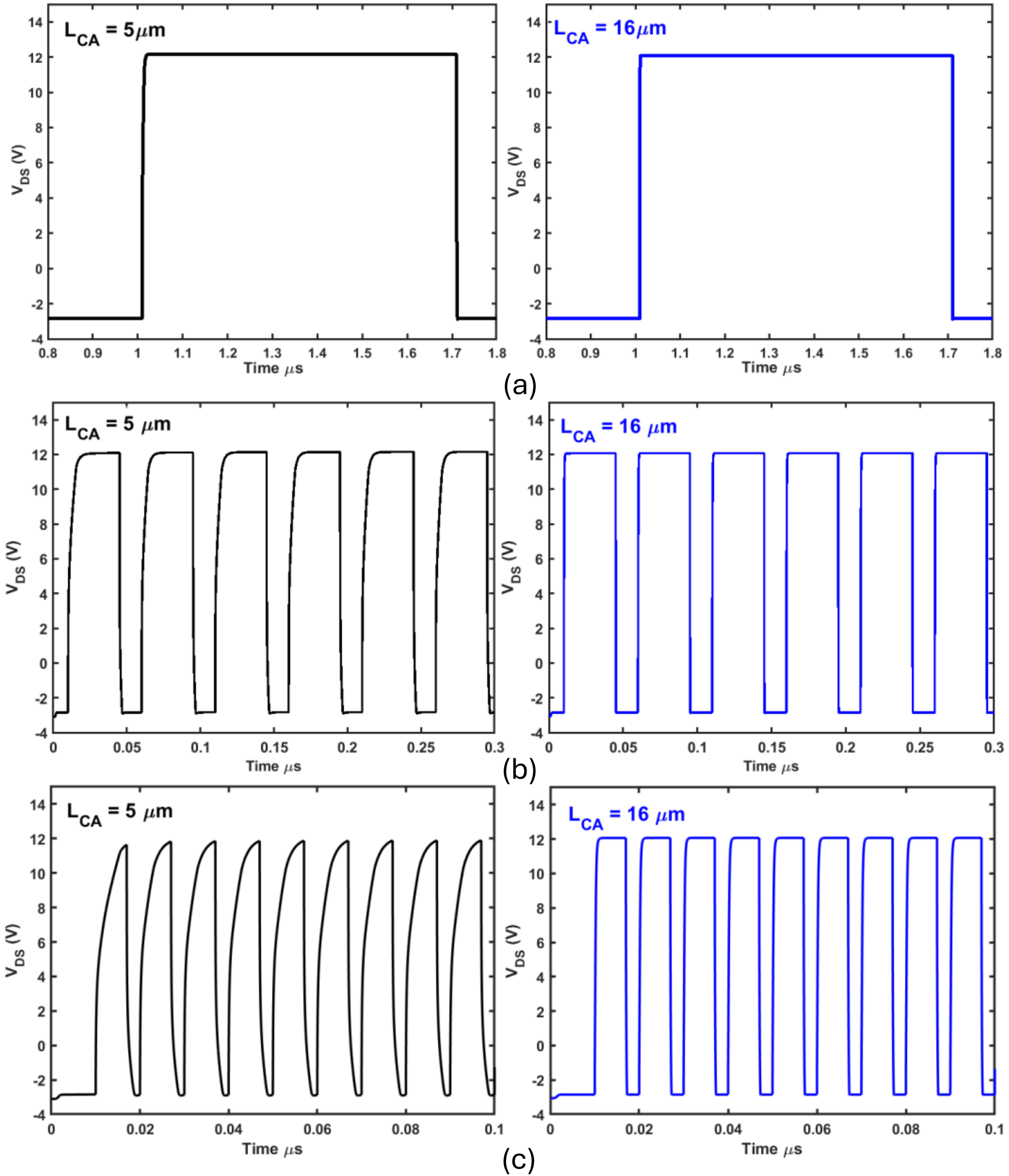
(a) Turn-on and (b) Turn-off voltage/current waveforms for different current aperture lengths of CAVET

- Both turn-on and turn-off time decreases with aperture length.
- Large aperture length has lower switching energy loss.



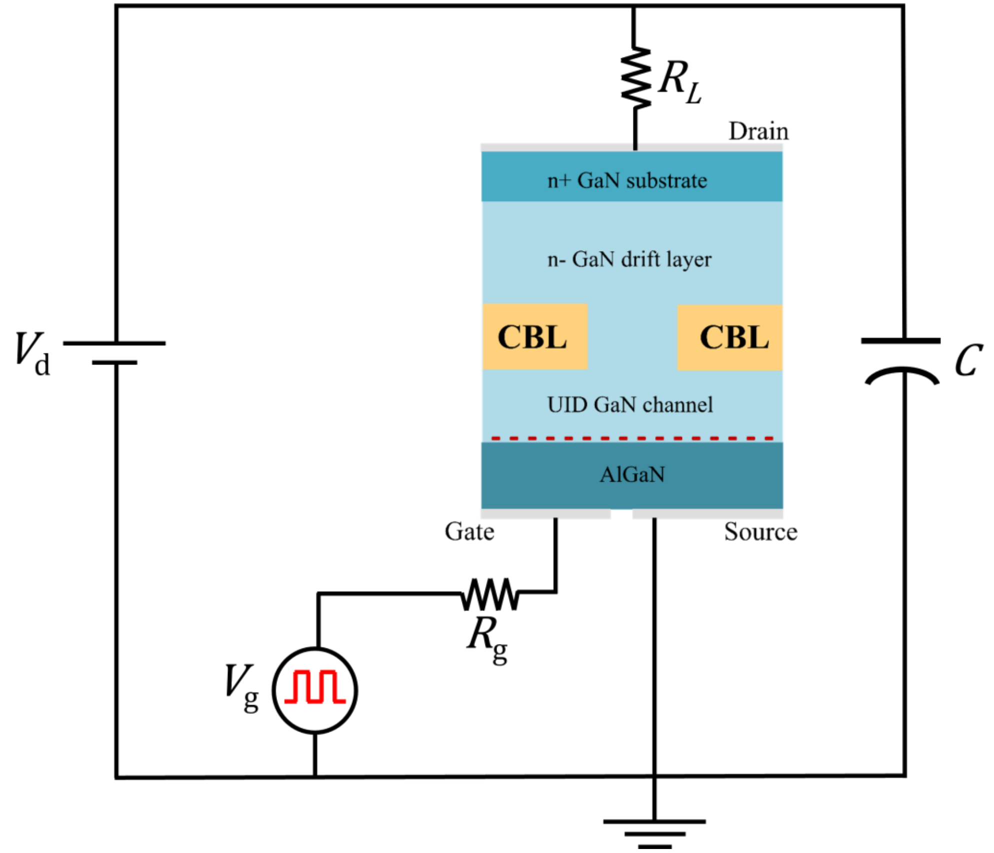
Switching Energy losses of the CAVET with various aperture lengths

Rectangular-wave oscillator circuit



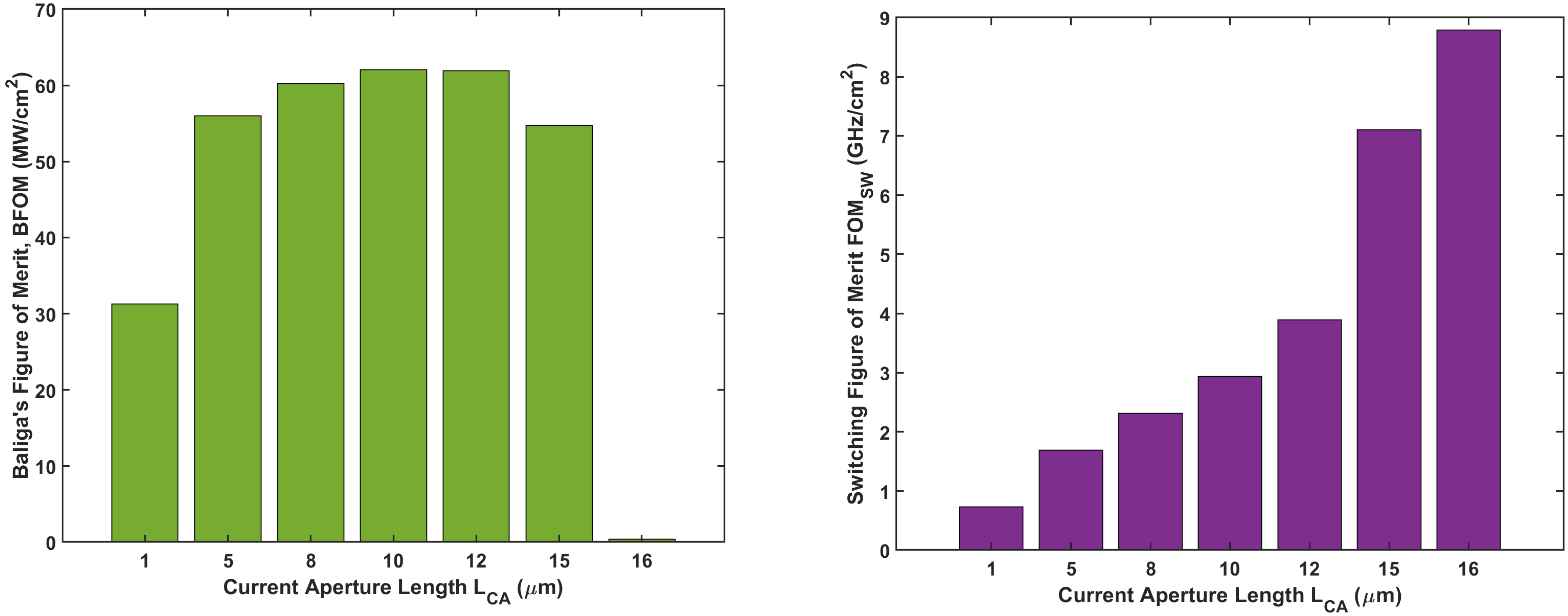
Typical waveforms of CAVET with various aperture length at switching frequencies of: (a) 1 MHz, (b) 20 MHz and (c) 100 MHz.

- Output waveform of oscillator remains sharp for larger aperture length at higher frequencies.



Schematic circuit diagram of a rectangular-wave oscillator circuit.

Figure of Merits

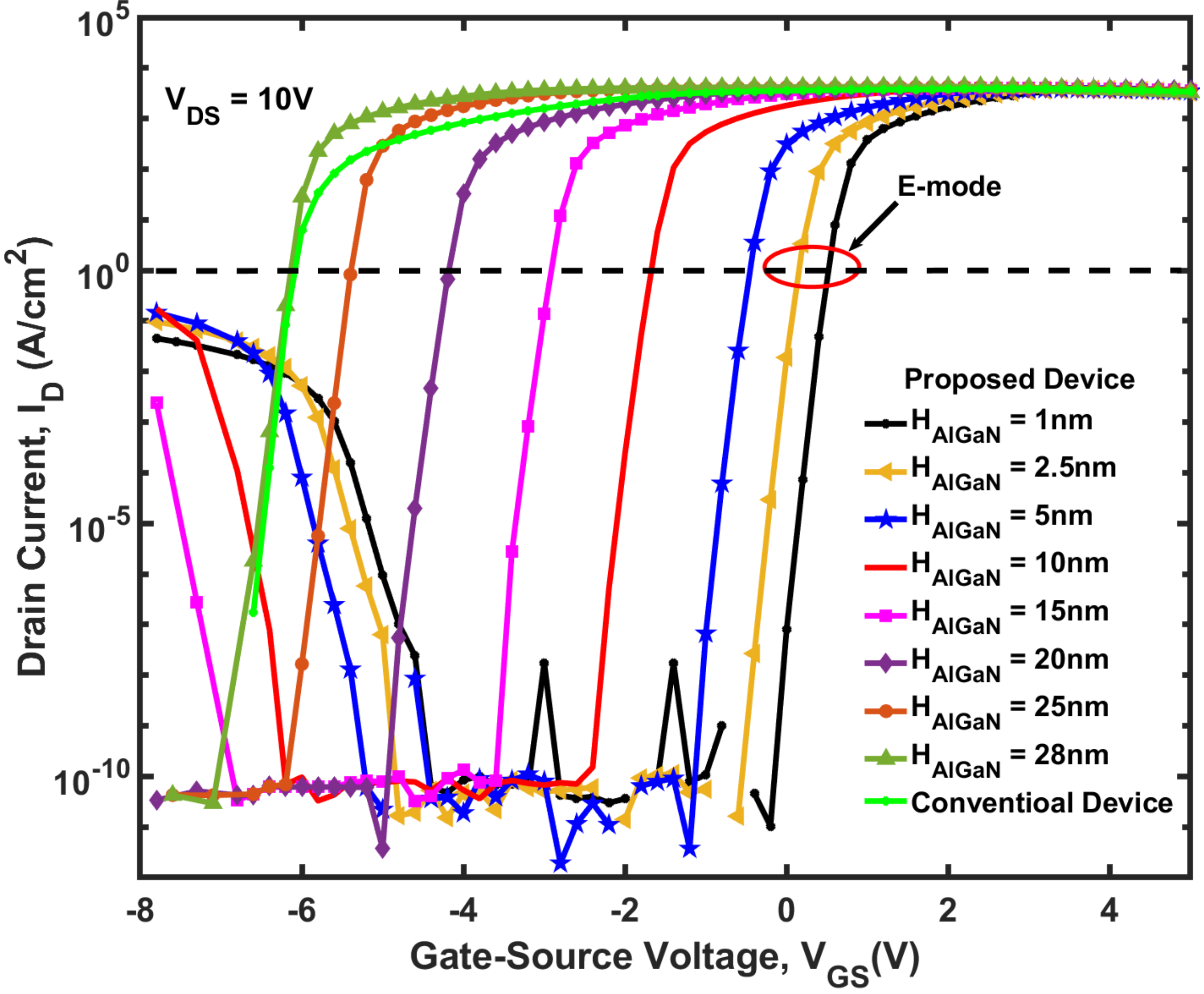


Comparison of Figure of Merits for various current aperture lengths of CAVET.

- Baliga’s Figure of Merit (BFOM) is highest for medium aperture length while Switching Figure of Merit (FOM_{SW}) is highest for large aperture length.
- Considering this trade-off Device with aperture length of 15 µm is best for high power switching applications.

Design of Vertical GaN Device with Superior Performance than Conventional Device

E-Mode Device



- By adjusting the parameters, an **E-Mode device** can be achieved.

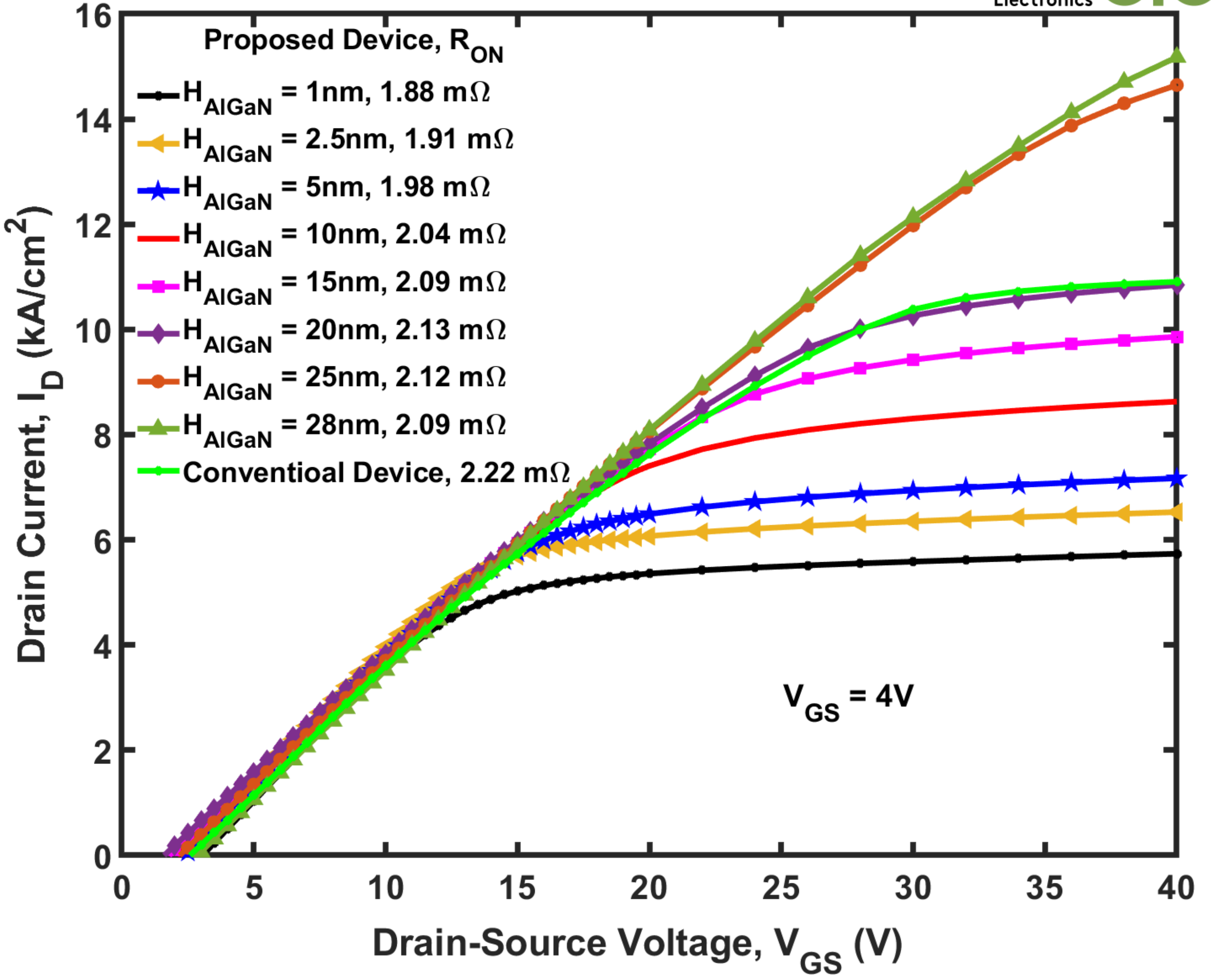
Transfer Characteristics of Conventional and proposed Device at logarithmic Scale

Optimization of On-state Resistance

- **On- Resistance :**

The conventional device is 2.22 mΩ.

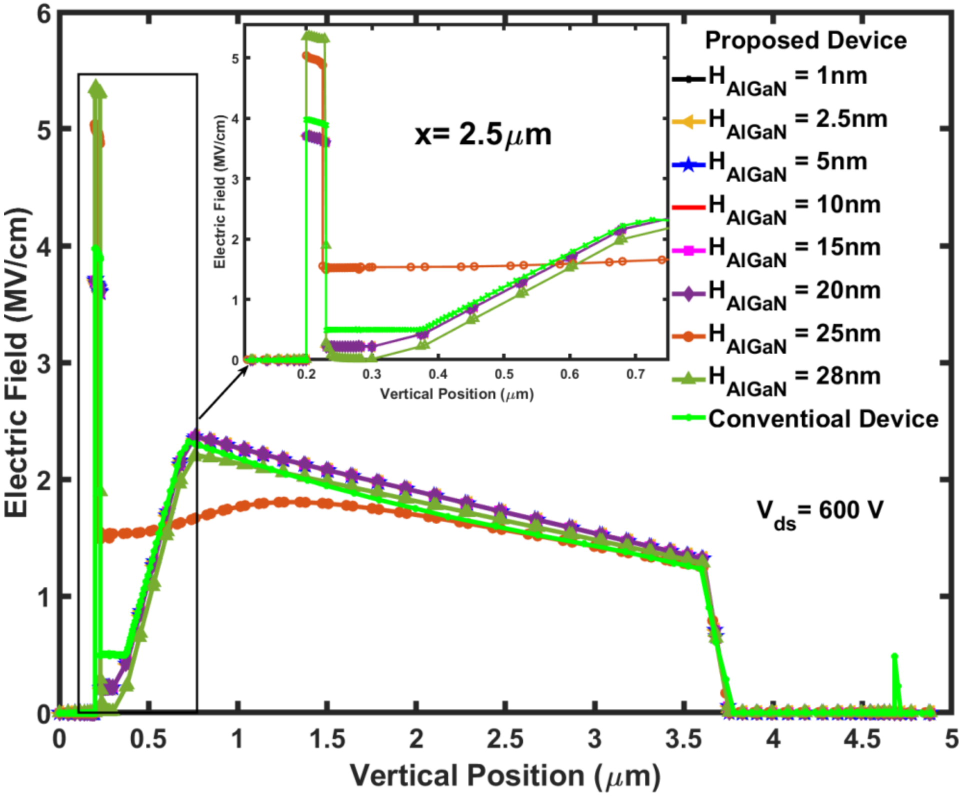
The proposed device is 1.88 mΩ.



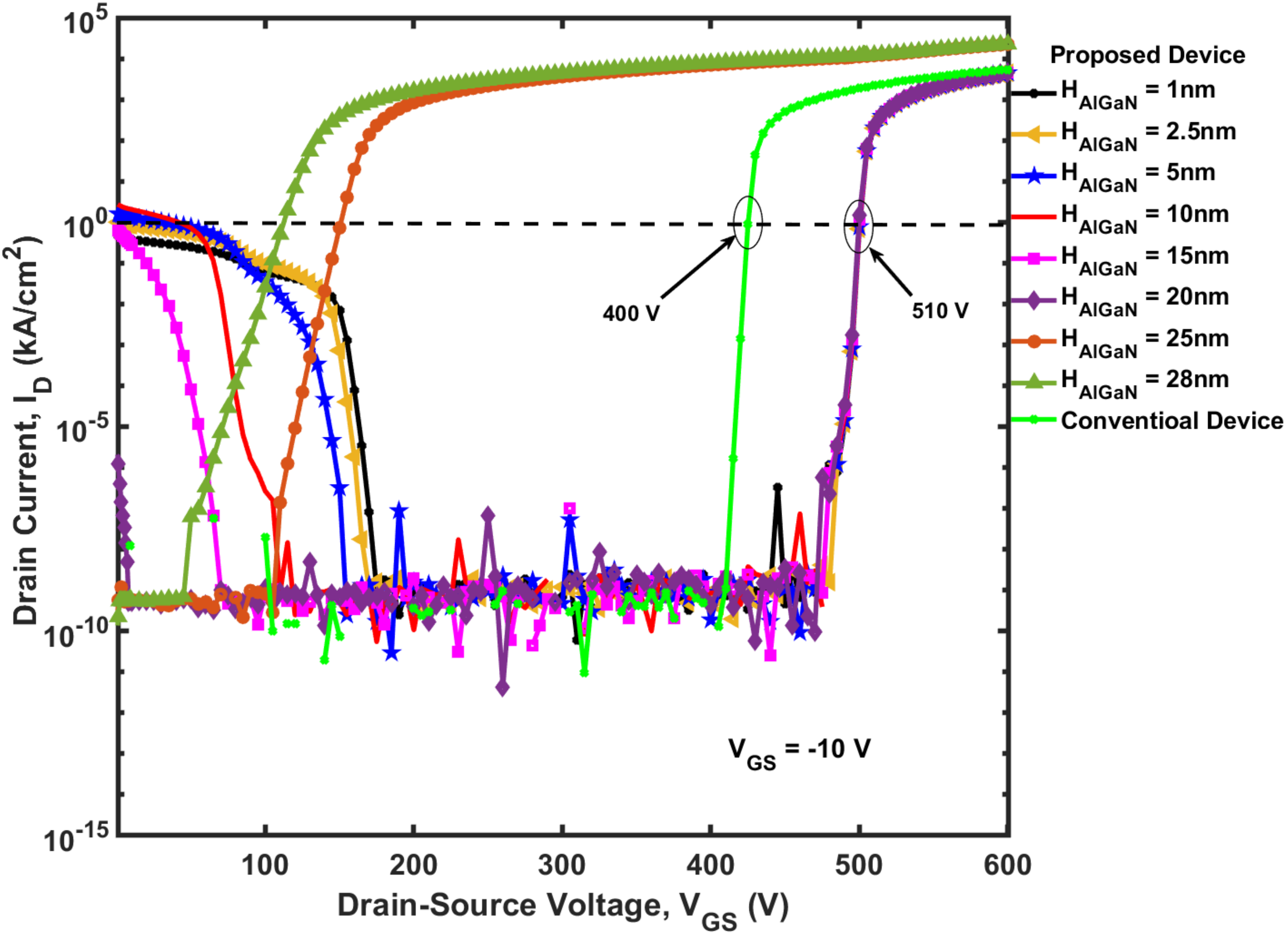
Output Characteristics of Conventional and proposed Device.

Breakdown Voltage Characteristics

- Addition to the reduced R_{on}, the breakdown voltage is improved to more than 100V than the conventional device.



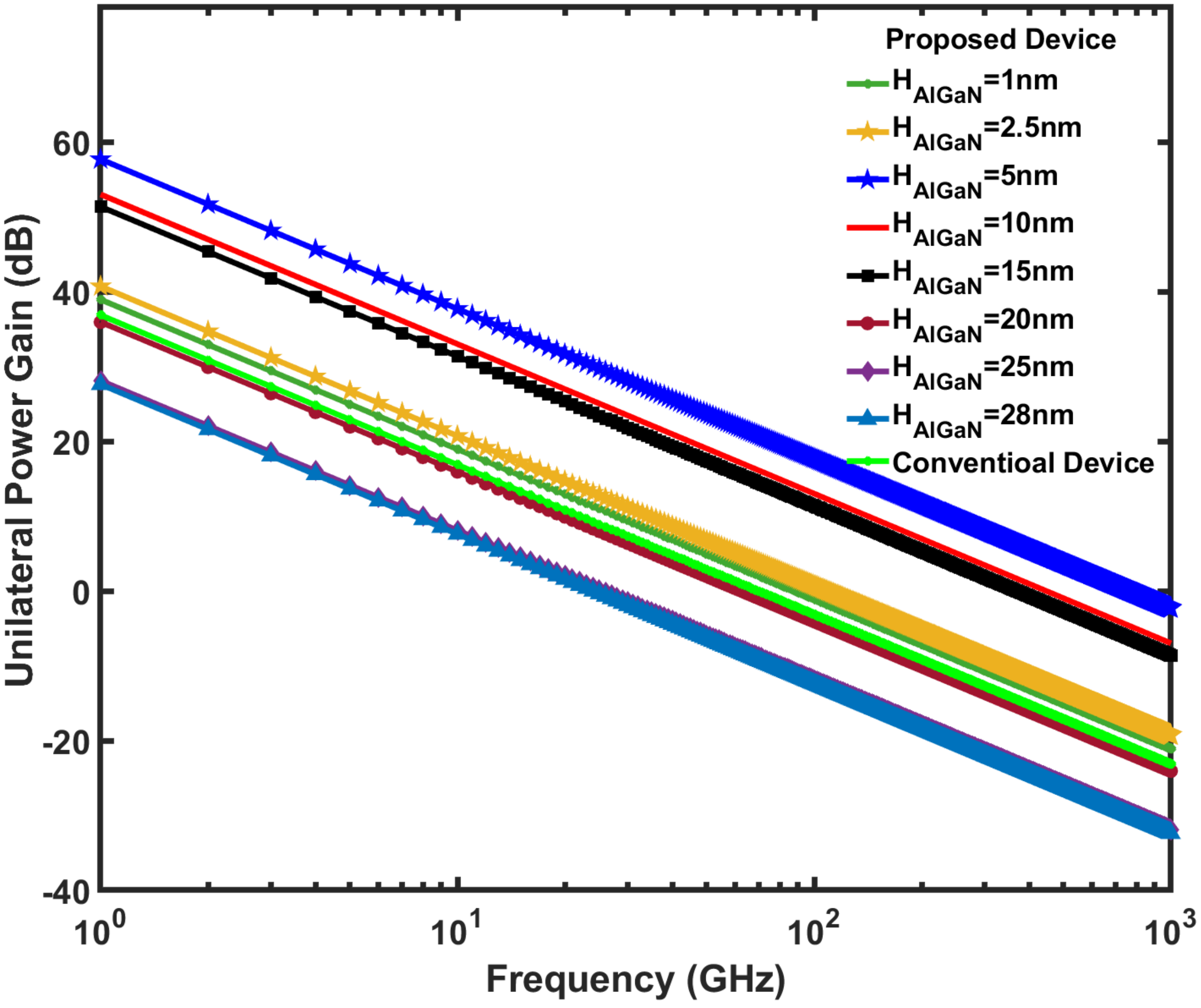
Electric Field Concentration



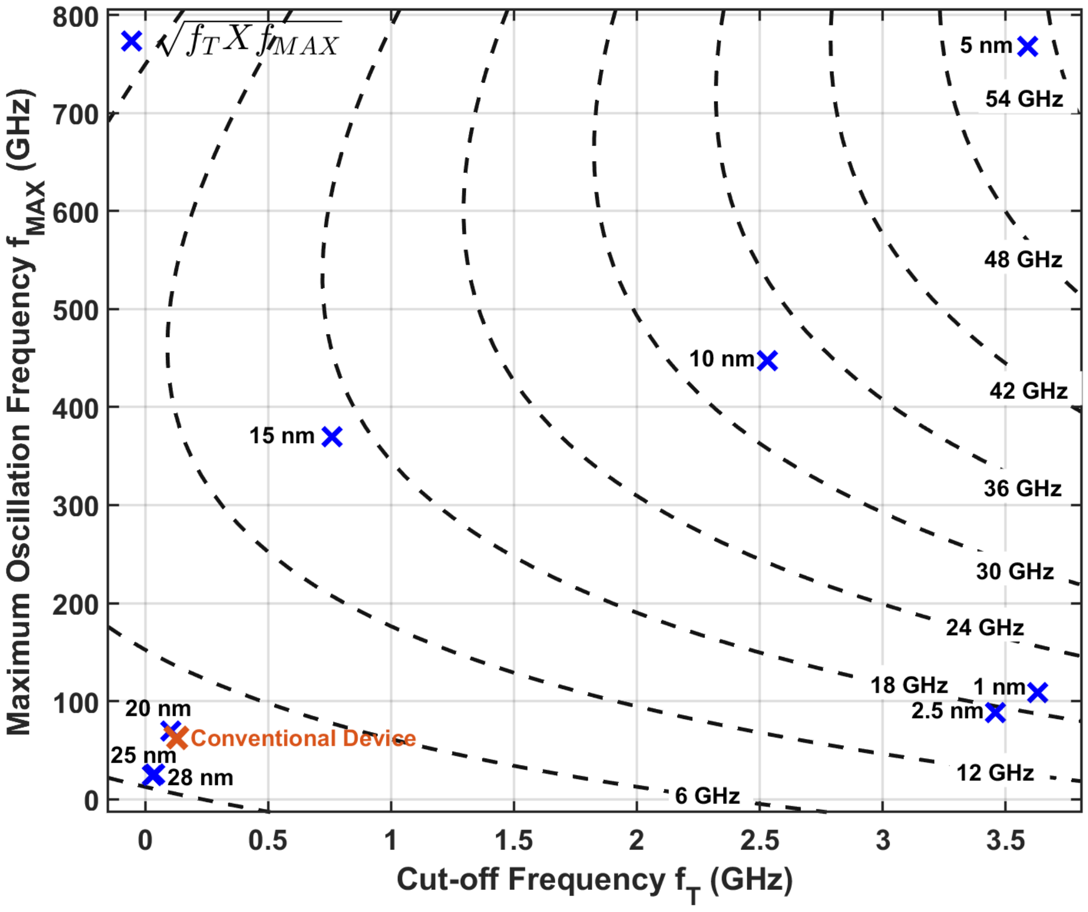
Breakdown Characteristics at Logarithmic Scale.

RF Characteristics

- Proposed device achieves a higher Unilateral power gain



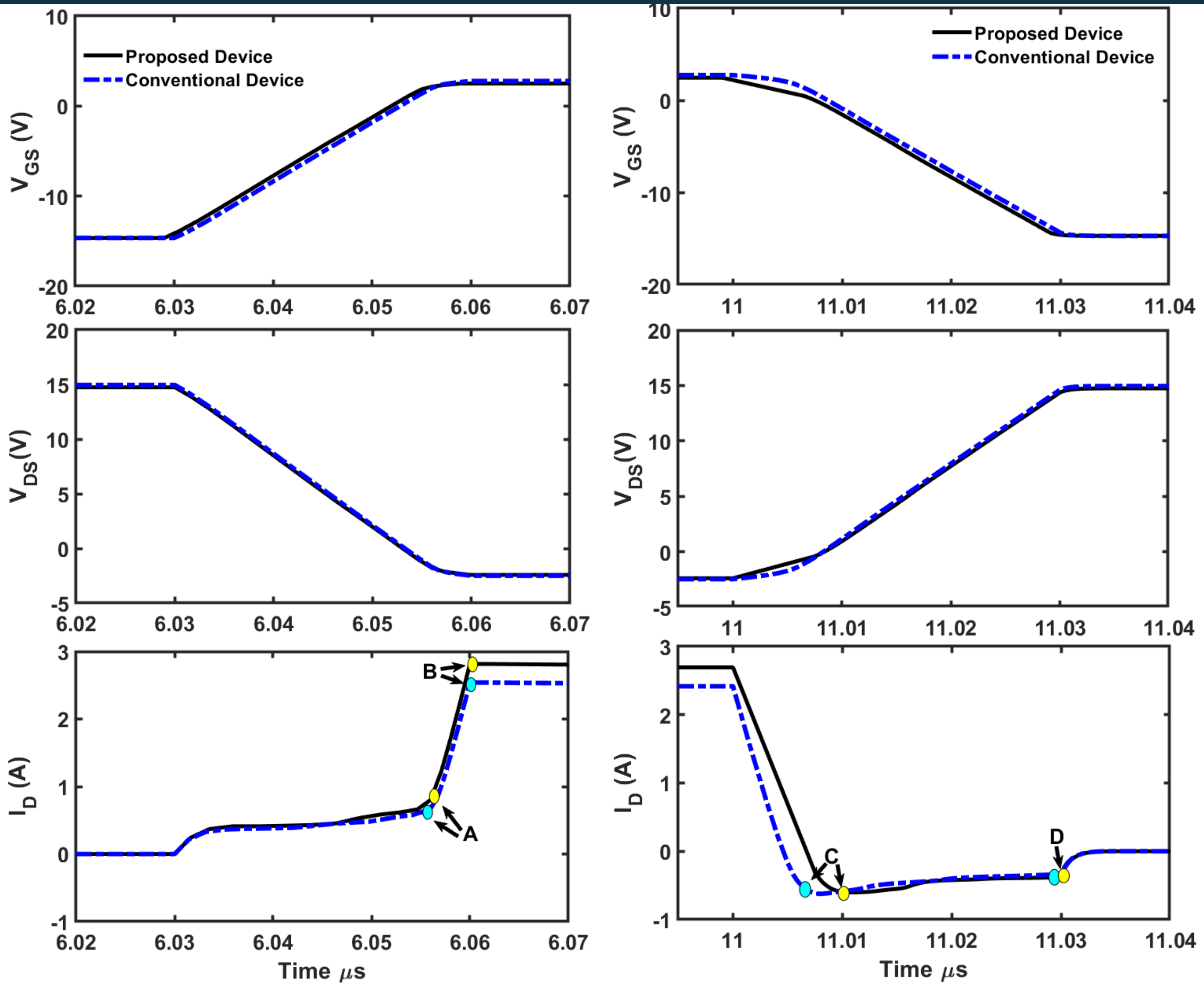
Unilateral power gain (U) versus frequency



f_{MAX} against f_T for proposed and conventional device

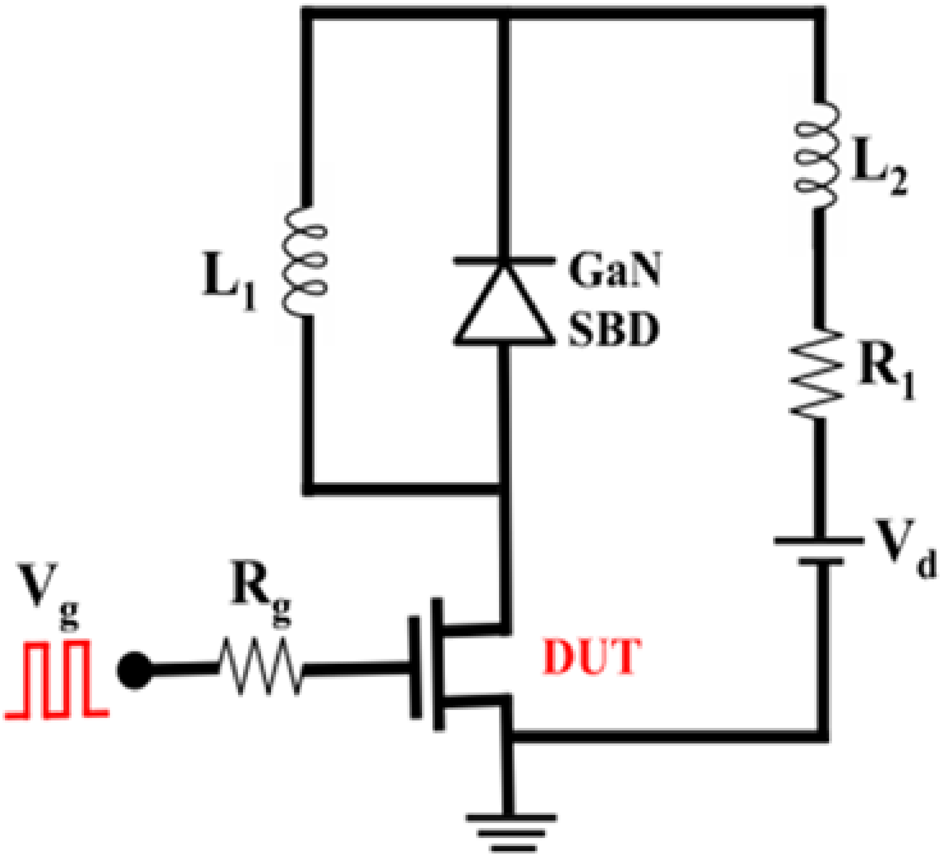
- For proposed device, the f_T and f_{MAX} values increase more than 15 and 10 times respectively.
- The $\sqrt{f_T \times f_{Max}}$ value increases almost 20 times.

Switching Characteristics



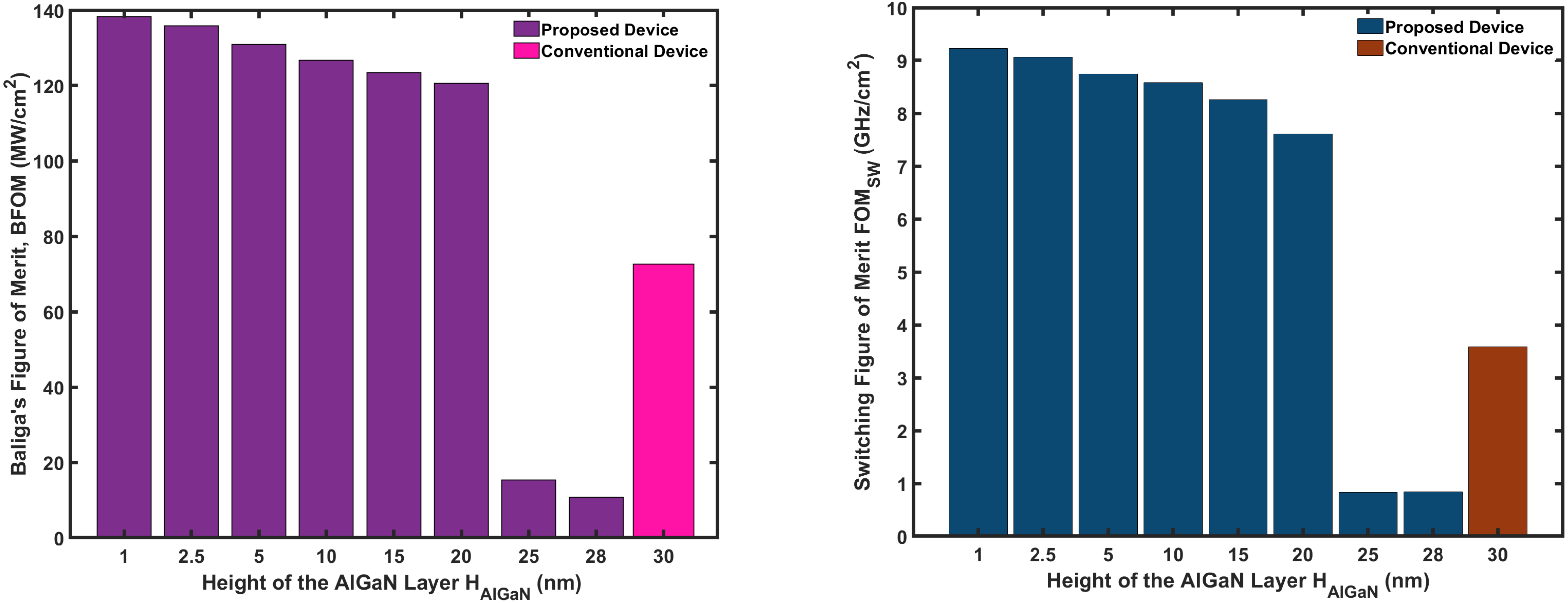
(a) Turn-on and (b) Turn-off voltage/current waveforms for proposed and conventional device

- Proposed device has lower switching time than the conventional device.



Switching test circuit

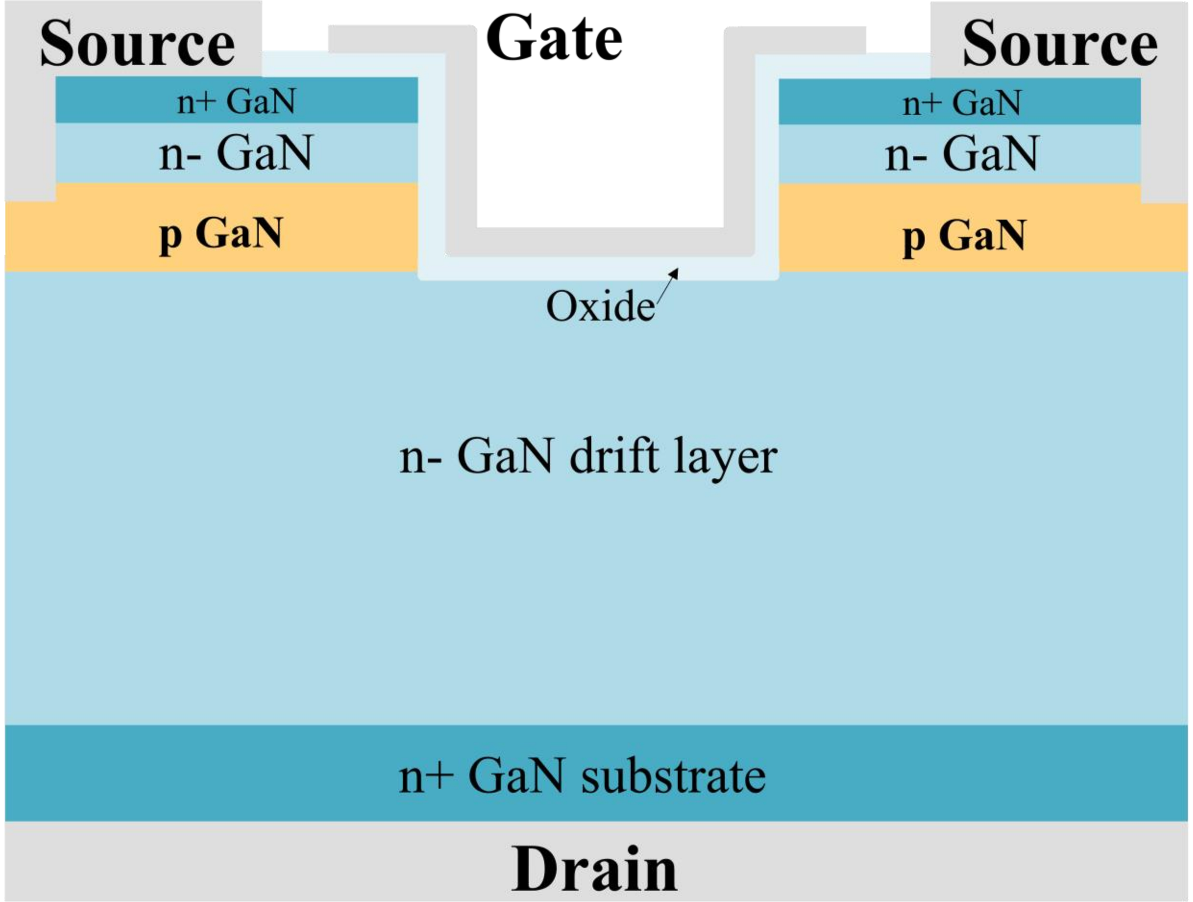
Figure of Merits



Comparison of Figure of Merits for proposed and conventional device.

- The Baliga's Figure of Merit (BFOM) and Switching Figure of Merit (FOM$_{SW}$) both are higher for proposed device than the Conventional Device.

Vertical Trench MOSFET (Fabricated)

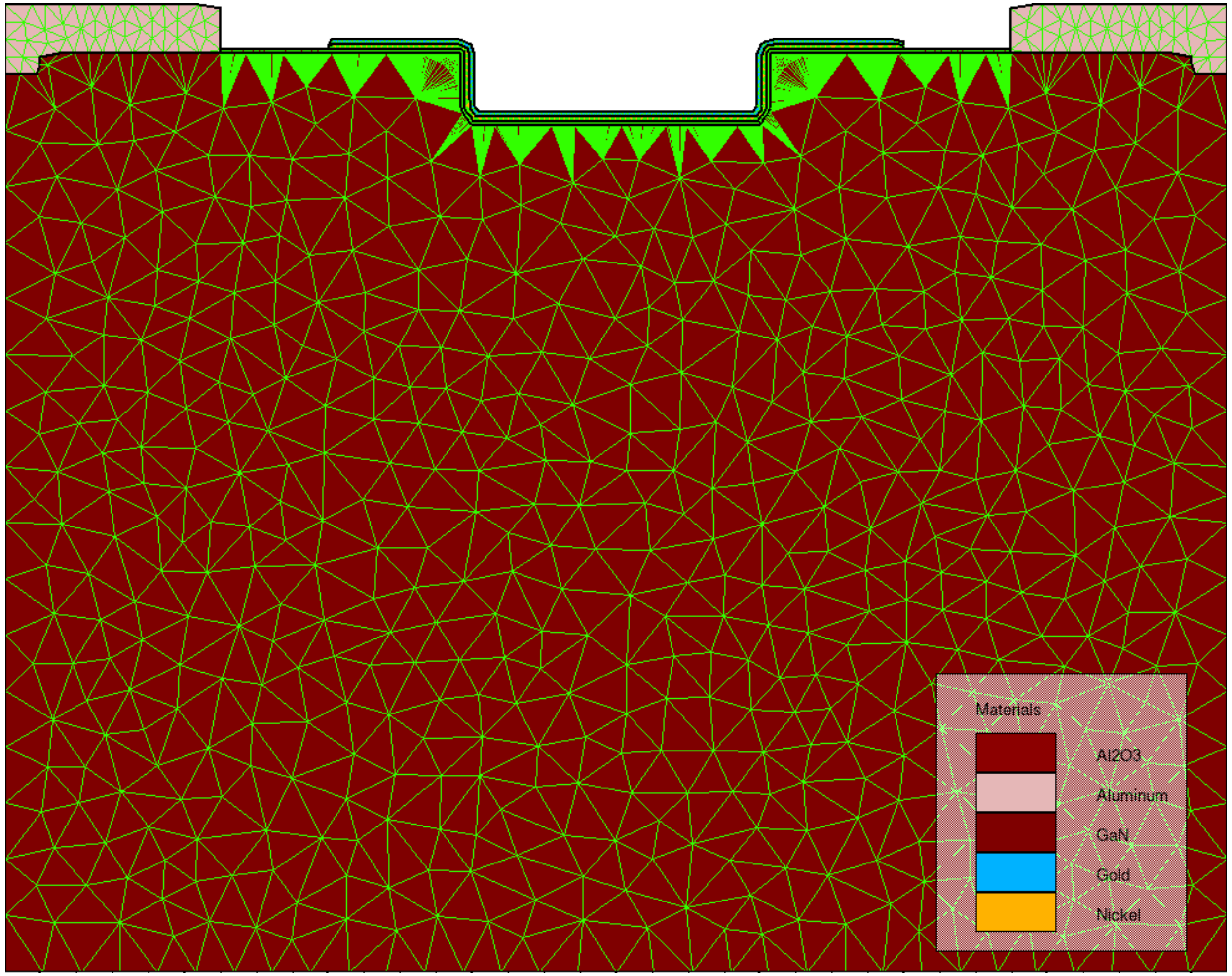


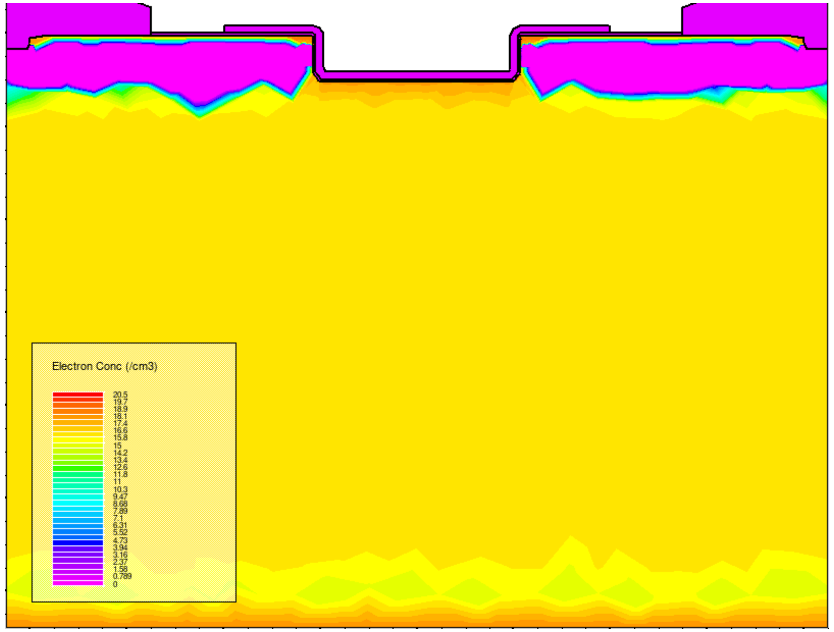
Faricated GaN Vertical Trench MOSFET

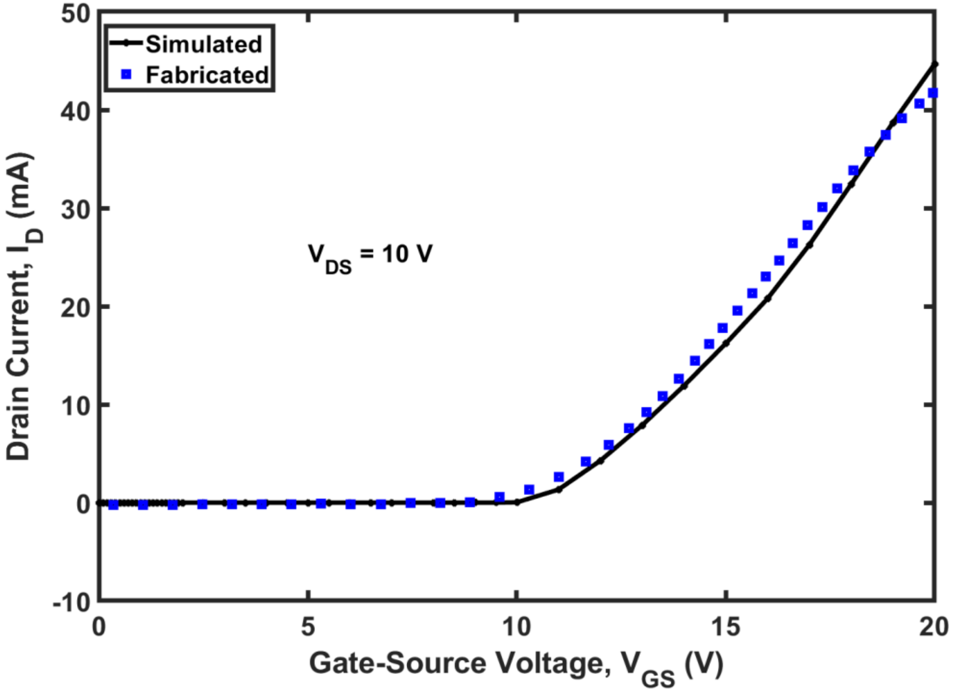
- The active area of the fabricated device is around $5.88 \times 10^{-4} cm^2$.
- The threshold voltage is around 10 V.
- The current density around Vgs=11V is 1.5 kAcm-2
- The on-state resistance is 5.8mΩcm2
- And the breakdown voltage of the device is 1.6kV.

M. Kamiński, A. Taube, J. Tarenko, O. Sadowski, E. Brzozowski, J. Wierzbicka, M. Zadura, M. Ekielski, K. Kosiel, and J. Jankowska-Śliwińska, “Vertical GaN Trench-MOSFETs Fabricated on Ammonothermally Grown Bulk GaN Substrates,” physica status solidi (a), pp. 2400077, 2023.

Vertical Trench MOSFET (Simulated)







Simulated GaN Vertical Trench MOSFET with meshing


THANK YOU!