The research in the Microwave Microelectronic Lab is focused on high power high frequency devices and ICs made of GaN and related wide bandgap semiconductors. These devices are capable of delivering record high power density, operating in a broad temperature range from cryogenic up to at least 300°C; they are robust and chemically stable. These features make GaM microwave devices best candidates to replacing many of existing components, from Si devices in power conversion systems to MEMS in microwave switches.

The group has demonstrated low loss high power microwave switches, power limiters and other devices and ICs which outperform most of existing traditional devices. The group also works on GaN based components for power electronic applications.
III-Nitride microwave switches

Grigory Simin

Department of Electrical Engineering, University of South Carolina, Columbia, SC
simin@cec.sc.edu
Microwave switches are essential components in nearly any modern RF and microwave systems.

**Microwave switch applications**

- **Microwave switches in 3G cell communications**
- **Satellite communications with on-board switching systems**
- **Reconfigurable phase-shifters in phased-array antennas**
- **Microwave switches in iPad**
- **Transmitter-receiver switches in radars**

- **Receiver**
- **Transmitter**
- **Switch**
III-N HFET is a new paradigm in RF switching

The AlGaN/GaN heterostructure induces 2DEG with sheet densities up to $5 \times 10^{13}$ cm$^{-2}$, forming a metal-like conducting plane.

MOSHFET RF switch concept

ON state
\[ V_G = 0 \]

OFF state
\[ V_G < V_T \]
State-of-the-art III-N MOSHFET

**AlGaN/GaN 2DEG:**

\[ \mu \approx 1800 \text{ cm}^2/\text{V-s} \]

\[ n_s \approx 1.5 \times 10^{13} \text{ cm}^{-2} \]

\[ R_{SH} \leq 230 \Omega \text{/Sq.} \]

<table>
<thead>
<tr>
<th>Device component</th>
<th>Insertion loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 µm S-D spacing, ( R_{SD} \sim 1.15 \Omega\text{-mm} )</td>
<td>(~ 0.1 \text{ dB-mm} )</td>
</tr>
<tr>
<td>Contact ( R_C \sim 0.5 \Omega\text{-mm} )</td>
<td>(~ 0.09 \text{ dB-mm} )</td>
</tr>
<tr>
<td>Total ( R_{ON} \sim 1.65 \Omega\text{-mm} )</td>
<td>(~ 0.2 \text{ dB-mm} )</td>
</tr>
<tr>
<td>3-mm gate periphery MOSHFET</td>
<td>(~ 0.065 \text{ dB} )</td>
</tr>
</tbody>
</table>
## MOSHFET vs. other RF switching devices

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Pin-diodes</th>
<th>RF MEMS</th>
<th>GaAs HEMTs</th>
<th>III-N MOSHFETs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>discrete devices</td>
<td>Planar – IC</td>
<td>Planar - IC</td>
<td>Planar – IC</td>
</tr>
<tr>
<td>Insertion loss</td>
<td>0.3…1.5 dB</td>
<td>0.1…5 dB</td>
<td>0.2…2.5 dB</td>
<td>0.05…1.5 dB</td>
</tr>
<tr>
<td>Isolation</td>
<td>&gt; 30 dB</td>
<td>&gt; 40 dB</td>
<td>&gt; 25 dB</td>
<td>&gt; 30 dB</td>
</tr>
<tr>
<td>Handling powers</td>
<td>&lt; 10 W</td>
<td>&lt; 1 W</td>
<td>&lt; 1 W</td>
<td>Up to 100 W</td>
</tr>
<tr>
<td>DC power consumption</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Biasing network</td>
<td>Requires LC filters</td>
<td>Simple</td>
<td>Simple</td>
<td>Low</td>
</tr>
<tr>
<td>Temperature, chemical, radiation stability</td>
<td>Poor</td>
<td>Poor</td>
<td>Mediocre</td>
<td>Excellent</td>
</tr>
<tr>
<td>Reliability</td>
<td>Good</td>
<td>Mediocre</td>
<td>Good</td>
<td>Excellent</td>
</tr>
</tbody>
</table>
Typical circuit for low-loss high isolation RF switch

Effect of $R_{ON}$ and $C_{OFF}$ on series/shunt RF switch IC performance

Higher $R_{ON}$:
- increases the insertion loss provided by the series device $D_1$
- decreases the isolation provided by the shunt device $D_2$

Higher $C_{OFF}$:
- increases the insertion loss provided by the shunt device $D_2$
- decreases the isolation provided by the series device $D_1$
III-N Single-pole, single-throw (SPST) switch MMIC

![Graph showing Insertion Loss (no metal loss) and Isolation vs Frequency. The graph includes a curve for Insertion Loss (no metal loss) and another for Insertion Loss (thin metal). The Isolation curve shows a gradual increase with frequency.]
III-N Single-pole, double-throw (SPDT) switch MMIC

Insertion loss and isolation of III-Nitride Single-pole double-throw integrated MOSHFET RF switch
III-N MOSHFET RF Switch maximum RF powers

**ON**
- HP ADS simulations
- Measured at 10 GHz

\[ P_{ON} \sim I_{DS}^2 \times R_L \]

**OFF**
- HP ADS simulations
- Measured at 10 GHz

\[ P_{OFF} \sim (V_G - V_T)^2 / R_L \]

Peak switching Power, dBm
Maximum switching power measured

RF power is limited by the available power source
III-N MOSHFET RF Switch temperature stability

Tested temperature range limited by the probe station specs
TLM data for MOSHFET RF switch at 77K and room temperature.

300K: $R_{sh}=268$ W/sq; $R_c = 0.45$ W×mm;
77K: $R_{sh}=92$ W/sq $R_c = 0.36$ W×mm;

Single shunt MOSHFET in a 50-W CPW.
RF transmission at room temperature and at 77K.
III-N MOSHFET RF Switch switching speed

100 ns pulses

- No large-signal RF dispersion (no current collapse)
- Switching time is driver-circuit limited (ns range expected)

50 µs pulses
Millimeter-wave III-N C$^3$-MOSHFET RF Switch

Ohmic contacts
- High-T annealing
- Tight Gate alignment

C$^3$ MOSHFET
- No annealed contacts
- Alignment-free technology
C³ HFET vs. regular HFET RF-switch

\[ V_G = 0 \text{ (ON) } \]

\[ V_G = -10 \text{ V (OFF) } \]

Transmission, dB

Frequency GHz

RF Input

RF Output

SiC

AlGaN

GaN

SiO₂
C^3 MOSHFET RF Switch MMIC

Small-signal

Insertion Loss

Isolation

Transmission (dB)

Pin (dBm)

ON

OFF

V_{G1} = 0

V_{G2} =

V_{G1} =

-12V

-16V

-20V

10 GHz CW

Frequency (GHz)
C³ – HfO₂ RF Switch

Experimental multigate RF switch ($W = 200 \, \mu m$, $L_G = 0.25 \, \mu m$)
Capacitively-coupled contacts ($C^3$) – no annealed ohmic contacts
Multigate C³- RF switches

C³ multigate RF switch (W = 200 mm, LG = 0.25 mm)

Side-Gated C$^3$ RF Switch

No gate electrode in the RF Input-output region
Side-gate electrode controls the impedance of C$^3$ contacts thus turning switch ON and OFF
Side-gated C³- series test element

Control electrode

W=50 µm

Experimental data and comparison with C³ - models
Side-gated C³- SPST

Single control electrode controls the ON/OFF state of the multi-finger C3-device
Side-gated C$^3$- SPST performance

**Insertion Loss, dB**

- 0.3 dB @ 6 GHz

**Isolation, dB**

- 27.5 dB @ 6 GHz

Small-signal insertion loss and isolation

Control electrodes bias

**ON-state:** $V_{\text{SER}} = 0; V_{\text{SHT}} = 10$V;

**OFF-state:** $V_{\text{SER}} = 10$V; $V_{\text{SHT}} = 0$;