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III-nitride transistors with capacitively coupled contacts

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Due to its vast applications potential, III-nitride wide band gap semiconductor technology is currently under aggressive development. Several research groups around the world are developing visible and UV light emitters and detectors and microwave transistors. To date nearly all the III-N high frequency electronic devices are based on two-dimensional (2D) electron gas (2DEG) channel at the AlGaN–GaN heterointerface first demonstrated in Ref. 1. Conventional device fabrication requires high-temperature annealed source-drain Ohmic contacts. There are several important issues associated with this design. The annealing temperatures (typically over 850 °C) degrade AlGaN–GaN heterojunction and generate trapping centers that degrade high frequency performance; high-temperature annealing and trapping centers may also significantly reduce the device reliability; the fabrication process for devices with Ohmic contacts involves multiple steps requiring precise alignment. Ohmic contacts are essentially needed for the devices employing dc to rf energy conversion, such as rf amplifiers, oscillators, etc. There is also a broad class of devices, which operation does not necessarily need the dc current. These are primarily the rf control devices such as switches, attenuators, modulators, power limiters, etc. These devices are key components of radars, wireless base stations, satellite communications, and many other high-frequency systems.2 3 Recently, high power rf switches made of AlGaN/GaN heterostructure field-effect transistors (HFETs) demonstrated a superior performance in terms of maximum power density, bandwidth, operation temperature, and high breakdown voltage, which made them excellent candidates for high power wireless systems.2 Even higher rf powers have been achieved using insulated gate AlGaN/GaN metal-oxide-semiconductor heterostructure field-effect transistors (MOSHFETs).5 6 All of the above devices used annealed Ohmic source and drain contacts.

In this letter we explore an alternative approach to fabricate high power rf control devices using capacitive coupling between the metal electrodes and the high-density 2DEG at the AlGaN/GaN interface. This type of coupling is efficient due to (i) very low 2DEG sheet resistance coming from record high sheet electron density of $>10^{13}$ cm$^{-2}$ and high 2D electron mobility and (ii) relatively thin barrier layers resulting in high electrode-2DEG capacitance. We show that capacitively coupled contact (C$^3$) design leads to low equivalent contact resistance at high frequencies. Importantly, we also show that C$^3$HFET and C$^3$MOSHFET devices have much higher operating rf powers as compared to HFETs. C$^3$ design is instrumental for studying the two-dimensional electron gas transport in other wide band gap heterostructures such as AlN/GaN, diamond, etc., where Ohmic contact fabrication is difficult. © 2006 American Institute of Physics.

FIG. 1. Cross-sectional view of the C$^3$MOSHFET.
transmission line model (TLM) pattern; we used them to extract the rf contact resistance. For this, the $S$ parameters of the test elements were measured using HP 8510C vector network analyzer. For comparison we have also fabricated regular HFET and MOSHFET devices with annealed Ohmic contacts with identical layouts.

The components of the measured C$^3$ MOSFET contact impedance are shown in Fig. 2. The obtained dependencies for the C$^3$ HFET look similarly and are not shown for the clarity of the graph. The equivalent contact resistance is represented by the real part of the input impedance. As seen, the equivalent contact resistance of the C$^3$ device is below 0.6–0.7 $\Omega$ mm in a broad frequency range of 2.5–25 GHz. It compares favorably with the values typical obtained for annealed Ohmic contacts in the AlGaN/GaN based HFETs (0.5–1 $\Omega$ mm). The reactance component is close to the real part at high frequencies above 15 GHz; thus it can be easily compensated by a simple matching circuit.

Fundamental advantage of proposed C$^3$ design over regular Ohmic contacts is related to the signal injection mechanism. In C$^3$ device, the rf signal injects from the metal electrode into active region via strong capacitive coupling that effectively shunts highly resistive AlGaN (or other wide band gap material) barrier layer. The vertical current component is purely capacitive; the lateral current component passes through low-resistive 2DEG channel; this results in overall low contact impedance. The rf properties of capacitively coupled contacts can be understood from the following model. In the C$^3$ transistor, the metal electrode and the 2DEG channel form an RC transmission line (inset in Fig. 2). The propagation constant $\gamma$ and the characteristic impedance $Z_0$ of the RC line are given by $\gamma=\sqrt{i2\pi f R_{sh} C_1}$ and $Z_0=1/W\sqrt{R_{sh} / (2\pi f C_1)}$, respectively. Here $R_{sh}$ is the sheet resistance of the 2DEG channel, $C_1$ is the metal-channel capacitance per unit area, and $f$ is the signal frequency. The equivalent contact impedance can be obtained as the input impedance $Z_{in}$ of the open-ended line as seen from the 2DEG channel side. The input impedance $Z_{in}$ is given by $Z_{in}=Z_0\cosh(\gamma L)$, where $L$ is the length of the metal electrode. The real and imaginary parts of $Z_{in}$ are plotted by solid and dashed lines, respectively, in Fig. 2. For capacitance calculations, we have used the dielectric permittivity of the AlGaN and SiO$_2$ layers $\varepsilon_{AlGaN}=9$ and $\varepsilon_{SiO_2}=3.9$, respectively. As seen, the simulated dependencies closely match our experimental data.

The following asymptotes are instructive for understanding the contact impedance of the C$^3$ device. In the low-frequency limit, $|\gamma L|<1$, the specific equivalent contact resistance of the C$^3$ device, $(R_{Ceq} W)\approx R_{sh} L / 3$ and the equivalent capacitance $C_{eq}=C_1 L W$, is the electrode geometrical capacitance. The most practically important case is the high-frequency limit: $|\gamma L| \gg 1$, or $f \gg 1/(2 \pi C_1 R_{sh})$, where $R_{sh}=R_{sh} L / W$ is the channel resistance under the contact and $C_0=C_1 L W$ is the electrode capacitance. In this case, the specific equivalent reactance and resonant reduce to $(R_{Ceq} W) \approx (|Z_{eq} W| \approx 0.71 \sqrt{R_{sh} / (2\pi f C_1)})$; they only depend on the $R_{sh}$ and $C_1$ and do not depend on the electrode length $L$. The high-frequency approximation for our C$^3$ MOSFET and C$^3$ HFET is valid at $f \gg 15$ GHz.

The role of rf control devices in various applications is to modulate the rf signals by applying a bias to the gate. Accordingly, the key requirements for these devices are the minimal insertion loss, the largest on/off rf transmission ratio and the highest operating rf powers. To assess these parameters, we characterized small-signal and high power rf performance of the C$^3$ transistors. The rf transmissions of the C$^3$ MOSFET and regular MOSFET are compared in Fig. 3. As seen, at $V_G=0$ V, when the 2DEG channel is open, the loss of C$^3$ MOSFET is lower than that of a MOSFET at frequencies above 2.5 GHz. This is despite that the C$^3$ MOSFET does not actually have Ohmic contacts. Note that no impedance matching was used for these measurements. For the impedance-matched C$^3$ MOSFET, the simulations show the rf loss as low as 0.15 dB mm (the dotted curve in Fig. 3 simulated for $W=200$ $\mu$m and $R_{Ceq}=0.6$ $\Omega$ mm). At the gate bias $V_G=10$ V, which is below the MOSFET threshold voltage $V_T=8$ V, the rf isolations of the C$^3$ MOSFET and regular MOSFET are close. These data show a superior high frequency performance of the C$^3$ MOSFET as compared to analogous device with Ohmic contacts. Very similar comparison was obtained for the C$^3$ HFET and HFET.

The rf power-handling capability of the C$^3$ MOSFET and C$^3$ HFET was characterized at 10 GHz (Fig. 4). For these experiments the gate bias $V_G$ was set below the threshold voltage $V_T$. As the input power increases, the rf isolation degrades. This degradation occurs because the input signal dynamically opens up the channel when the signal polarity is negative. For the devices in comparison, the maximum rf power $P_{max}$ was taken as the input power causing 1 dB degradation of rf isolation. As seen from Fig. 4, the maximum rf powers for the C$^3$ devices are much higher for the same gate bias offset. The mechanism responsible for the higher rf
powers is related to rf voltage across the capacitively
coupled contact. When the input signal goes negative, the
voltage across the capacitively coupled source increases and
depletes the channel under it. This also prevents forward gate
biasing thus further increasing the impedance. The
C3MOSHFET demonstrates the highest rf powers. This is
related to much lower gate currents and lower capacitance of
the MOSHFET structure leading to more effective channel
modulation. Assuming a parabolic dependence of $P_{\text{max}}$ on
the gate bias offset $V_G - V_T$, the $P_{\text{max}}$ dependence for the
C3MOSHFET can be approximated as $P_{\text{max}} \approx 0.26(V_G - V_T)^2$. One can see that for $V_G - V_T = 20$ V, the
C3MOSHFET $P_{\text{max}}$ exceeds 100 W, whereas for the regular
HFET or MOSHFET it is below 5 W for the same bias con-
ditions. At zero gate bias, the difference in the maximum rf
powers for the C3 and regular devices was less than
0.5–1 dBm.

The above results show that for typical AlGaN/GaN het-
terostructures, the C3 design offers a superior rf performance
compared to annealed contacts. It becomes even more attrac-
tive for high Al-content heterostructures and other wide band
gap devices (e.g., diamond based) where Ohmic contact for-
mation is extremely challenging. Lower barrier thickness and
larger band gap offsets in heterostructures with wide band
gap barriers result in higher $C_1$ values and higher 2DEG
density leading to even lower $R_{C,G}$. This makes the C3 devices
a useful tool to extract the 2DEG transport properties from
the $S$ parameters.

In summary, we presented Schottky- and insulated
gate-transistor designs using capacitively coupled contacts.
These devices do not require Ohmic contacts and can be fab-
ricated using gate alignment-free technology. As com-
pared to HFETs with Ohmic contacts, the C3 devices feature
low rf contact resistance, lower rf insertion loss, and remark-
ably high rf powers. This makes C3HFETs and
C3MOSHFETs attractive for various high power rf control
applications. The proposed design is instrumental for study-

Fig. 4. Maximum blocking rf power of the C3HFET and C3MOSHET in
comparison with regular devices. The maximum power was taken as the
input power at 1 dB rf isolation degradation.


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