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III-Nitride Transistors with Capacitively Coupled Contacts

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III-nitride transistors with capacitively coupled contacts

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AlGaN/GaN heterostructure field-effect transistor design using capacitively coupled contacts (C^3HFET) is presented. Insulated-gate [C^3 metal-oxide-semiconductor HFET (C^3MOSHFET)] has also been realized. The capacitively coupled source, gate, and drain of C^3 device do not require annealed Ohmic contacts and can be fabricated using gate alignment-free technology. For typical AlGaN/GaN heterostructures, the equivalent contact resistance of C^3 transistors is below 0.6 Ω mm. In rf-control applications, the C^3HFET and especially the C^3MOSHFET 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.
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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.[4] 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^3HFET and C^3MOSHFET devices have much higher rf power handling capability as compared to regular devices with annealed Ohmic contacts. The proposed approach is also very instrumental for studying the transport properties of 2DEG in other wide band gap materials and heterostructures, e.g., AlN, high Al-content AlGaN/GaN, diamond, etc., where the Ohmic contact fabrication presents the major obstacle.

The C^3HFET consists of three metal electrodes (source, gate, and drain) deposited on top of AlGaN/GaN heterostructure; the insulated gate modification (C^3MOSHFET) shown in Fig. 1 has an additional thin SiO_2 layer under the metal. To fabricate C^3 devices, the 20 nm thick $Al_{0.25}Ga_{0.75}N$ barrier layer was grown by metal-organic chemical vapor deposition (MOCVD) over 1.5 μm thick undoped GaN buffer layer on sapphire substrate. The 10 nm thick SiO_2 layer was formed by plasma-enhanced chemical vapor deposition (PECVD). The mesas were formed using reactive ion etching. The Ni/Au electrodes were patterned using optical photolithography; no annealing was used in device fabrication. Both C^3HFETs and C^3MOSHFETs had the same layout: the length of the source and drain electrodes $L=7$ μm, the gate length $L_G=1$ μm, the source-drain spacing $L_{DS}=5$ μm, and the device width $W=200$ μm. The 2DEG sheet resistance $R_{sh}=300$ Ω was found from on-wafer resistance mapping measurements. The threshold voltages were −5 and −8 V for the HFET and MOSHFET, respectively. To measure the equivalent rf contact resistance, we also fabricated ungated test elements with the source-drain spacing ranging from 2 to 6 μm. These elements formed the rf analog of

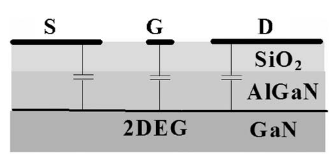

FIG. 1. Cross-sectional view of the C^3MOSHFET.

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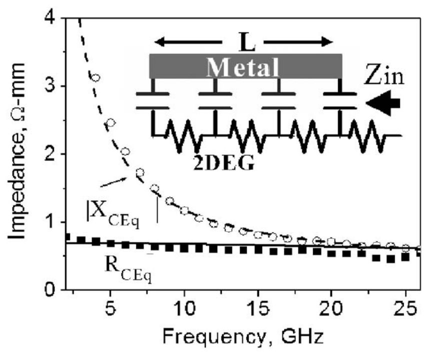

FIG. 2. Frequency dependence of the C^3MOSHFET specific contact impedance. Squares and circles—experimental contact resistance and reactance, respectively. Solid and dash lines—simulated dependencies. The inset shows the equivalent circuit of the capacitively coupled contact.

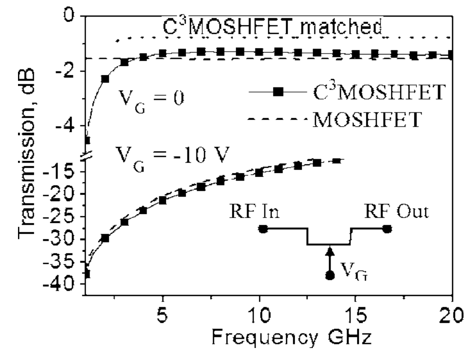

FIG. 3. Small-signal rf transmission of the C^3MOSHFET and MOSHFET at different gate biases. The dotted line shows the simulated transmission for the impedance-matched device at zero gate bias.

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^3MOSHFET contact impedance are shown in Fig. 2. The obtained dependencies for the C^3HFET 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 Ω 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 Ω 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 γ and the characteristic impedance Z_0 of the RC line are given by $\gamma=\sqrt{i2\pi f R_{sh} C_1}$ and $Z_0 = 1/W\sqrt{R_{sh}/(i2\pi f C_1)}$, 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 $Z_{in} = Z_0 \coth(\gamma L)$, 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 $\varepsilon_B=9$ and $\varepsilon_{ox}=3.9$, 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, $|\gamma L| \ll 1$, the specific equivalent contact resistance of the C^3 device, $(R_{C_{eq}}W) \approx R_{sh}L/3$ and the equivalent capacitance $C_{eq} \approx C_1 LW$, is the electrode geometrical capacitance. The most practically important case is the high-frequency limit: $|\gamma L| \gg 1$, or $f \gg 1/(2\pi C_0 R_0)$, where $R_0 = R_{sh}L/W$ is the channel resistance under the contact and $C_0 = C_1 LW$ is the electrode capacitance. In this case, the specific equivalent resistance and reactance reduce to $(R_{C_{eq}}W) \approx (|X_{C_{eq}}|W) \approx 0.71\sqrt{R_{sh}/(2\pi f C_1)}$; 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^3MOSHFET and C^3HFET 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^3MOSHFET and regular MOSHFET are compared in Fig. 3. As seen, at $V_G=0$ V, when the 2DEG channel is open, the loss of C^3MOSHFET is lower than that of a MOSHFET at frequencies above 2.5 GHz. This is despite that the C^3MOSHFET does not actually have Ohmic contacts. Note that no impedance matching was used for these measurements. For the impedance-matched C^3MOSHFET, 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 $R_{C_{eq}} = 0.6\ \Omega$ mm). At the gate bias $V_G=-10$ V, which is below the MOSHFET threshold voltage $V_T=-8$ V, the rf isolations of the C^3MOSHFET and regular MOSHFET are close. These data show a superior high frequency performance of the C^3MOSHFET as compared to analogous device with Ohmic contacts. Very similar comparison was obtained for the C^3HFET and HFET.

The rf power-handling capability of the C^3MOSHFET and C^3HFET 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.[7] 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

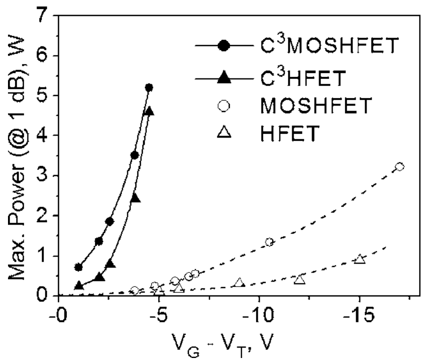

FIG. 4. Maximum blocking rf power of the C[3]HFET and C[3]MOSHFET in comparison with regular devices. The maximum power was taken as the input power at 1 dB rf isolation degradation.

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 C^3MOSHFET 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_{max} on the gate bias offset $V_G - V_T$,[7] the P_{max} dependence for the C^3MOSHFET can be approximated as $P_{max} \approx 0.26(V_G - V_T)^2$. One can see that for $V_G - V_T = 20$ V, the C^3MOSHFET P_{max} exceeds 100 W, whereas for the regular HFET or MOSHFET it is below 5 W for the same bias conditions. At zero gate bias, the difference in the maximum rf powers for the C^3 and regular devices was less than 0.5–1 dBm.

The above results show that for typical AlGaN/GaN heterostructures, the C^3 design offers a superior rf performance compared to annealed contacts. It becomes even more attractive for high Al-content heterostructures and other wide band gap devices (e.g., diamond based) where Ohmic contact formation 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 $R_{C_{eq}}$ This makes the C^3 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 fabricated using gate alignment-free technology. As compared to HFETs with Ohmic contacts, the C^3 devices feature low rf contact resistance, lower rf insertion loss, and remarkably high rf powers. This makes C^3HFETs and C^3MOSHFETs attractive for various high power rf control applications. The proposed design is instrumental for studying the transport properties of 2DEG in other wide band gap materials and heterostructures, e.g., AlN/GaN, high Al-content AlGaN/GaN, diamond, etc., where the Ohmic contact formation presents the major obstacle.

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