AlGaN/GaN field effect transistor with two lateral Schottky barrier gates towards resonant detection in sub-mm range

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Abstract

We report on the investigations of AlGaN/GaN field effect transistors with two lateral Schottky barrier gates on the sides of the two-dimensional electron gas. This kind of ‘EdgeFET’ allowed us to efficiently control the current flow in the 2DEG conduction channel. Moreover, due to depletion, regions at a certain range of reverse biasing form a nanowire, which is beneficial for the adjustable resonant THz detection. Our studies of DC characteristics and photoresponse in the sub-terahertz frequency confirm the validity of the approach.

Keywords: lateral Schottky contact, terahertz detectors, field effect transistors

(Some figures may appear in colour only in the online journal)

Introduction

Field effect transistors (FETs) can work as THz detectors. FETs with a wire channel (presented in the current study) are of even bigger interest because of hopes for resonant terahertz detection. As was predicted in the 1990s [1], FETs can be used as detectors in the terahertz frequency range due to nonlinearities related to plasma wave excitations in two-dimensional electron gas (2DEG). Among various detectors proposed and realized for the THz/sub-THz spectral region (such as bolometers, Golay cells, pyroelectrics, etc), THz detectors based on the excitation of plasma waves in 2DEG of FETs are among the most attractive ones, as they promise the development of large-scale integrated devices based on conventional integration technologies. Also FET detectors have advantages of short response time ($<10^{-9}$ s), wide range of operating temperatures (4–340 K), high frequency range, and low noise equivalent power (NEP $\sim 10^{-10}$ W/Hz$^{1/2}$). These parameters are comparable to the best current commercial room temperature THz detectors [2].

Detectors of such a type can operate in two regimes: resonant and non-resonant. The main criterion that defines a work regime of the detector is the $\omega \tau$ product, where $\omega$ is the fundamental plasma oscillation frequency and $\tau$ is the momentum relaxation time. When $\omega \tau > 1$, the FET operates as a resonant detector, with maxima at the plasma oscillation frequency. In the opposite case $\omega \tau < 1$, plasma oscillations are overdamped and the FET response is a smooth function of $\omega$ as well as of the gate voltage $V_G$ (non-resonant regime). In this regime, the responsivity of FETs as detectors is broadband and
similar to standard Schottky diodes [3]. One of the advantages of the resonant regime is a much greater responsivity than that of Schottky diodes [1].

Resonant detection of terahertz radiation by two-dimensional plasma waves was experimentally demonstrated using GaAs/AlGaAs based FETs [4–6], InAlAs/InGaAs based FETs [7–9], and double quantum well FETs at cryogenic [4] and room temperatures [10]. Despite this fact, the responsivity and resonant detection quality factors were still much smaller than the theoretical predictions. The smaller responsivity and wider resonant peak are mainly due to the following reasons: (i) an existence of oblique modes as was shown in [11, 12] and (ii) a plasmon leakage from gated regions to ungated channel regions of the FET [13]. As for the first assertion, commonly manufactured FETs have the width of the channel (W) significantly greater than the channel length (L), allowing for modes that propagate in the 2DEG channel at different angles and make the resonant peak wider. As for the second assertion, gated regions of the FET channel covered by gate metal significantly affect the plasma oscillation spectrum of detectors. In this case, resonant plasma frequencies dramatically decrease with an increase of cap region surface (theoretically described in [13]).

The simplest method to minimize the first effect is to create a narrow channel FET, i.e. FET with the channel width much smaller than the gate length (W ≪ L). There are a few technical solutions for this kind of FETs. One was demonstrated on GaN/AlGaN by using e-beam lithography and a complicated fabrication process to achieve a wire-shaped 2DEG [14]. However, such an approach still did not lead to the non-resonant detection of high quality as was shown in [15]. That was possibly due to the degradation of the carrier’s mobility as a result of the surface scattering in a small-dimension channel.

For solving this problem, we suggest to use a fin-shaped channel field effect transistor (FinFET) with two lateral Schottky barrier (LSB) gates, with gate metallization deposited directly to the edges of the transistor channel (figure 1(a)). This is in contrast to standard FinFET design (figure 1(b)), where the gate metallization is deposited both on the top and on the sides of the fin. We suggest EdgeFET as a short name for this device. The design of an EdgeFET structure allows us to control the channel width W by the gate voltage and to minimize the effect of the oblique modes while preserving the channel mobility.

The first theoretical and experimental study of LSB with interface 3D-metal/2DEG was performed by Peatman et al [16]. Following this case one can obtain 1D Schottky diode that combines the following useful features: (i) a small contact capacitance (C) due to an extremely small 1D contact area, (ii) a very low access resistance (R) due to a direct contact to 2DEG, and (iii) excellent transport properties of the 2DEG. As a result, one minimizes the parasitic RC constant of the Schottky junction.

**Device fabrication**

AlGaN/GaN heterostructure was used for both EdgeFET and FinFET structures. Gallium nitride (GaN) provides the highest electron saturation velocity, has a high breakdown voltage and operates in a wide range of temperatures [17, 18]. Thus this material has the biggest frequency-power performance potential among commonly used semiconductors. GaN based devices have been already demonstrated as terahertz detectors by several groups [19–22]. Recent experimental studies [23] of AlGaN/GaN HEMT photoresponses observe a saturation at intensities of the NH₃ laser >20 kW cm⁻² (with 100 ns pulses at 1.1 THz) that is a few times higher than for Si- or GaAs-based transistors [24]. References [25, 26] demonstrated an application of GaN/AlGaN-based FET terahertz detectors for characterization of terahertz pulses and for use in spectroscopic systems with low-repetition-rate pulses.

The AlGaN/GaN structures were grown by metalorganic vapour phase epitaxy (MOVPE) method in the closed coupled showerhead 3 × 2 inch Aixtron reactor. The epistucture consisted of 2 nm GaN-cap, 26.3 nm Al₀.₁₅Ga₀.₈₅N barrier layer, 0.7 μm intentionally undoped GaN layers and 1 μm high resistive GaN:C buffer. All epilayers were grown on the c-plane sapphire substrate. The device processing was performed using a commercial laser writer system for lithography process with the 375 nm laser source.
At the first step of sample processing, the shallow mesas were etched by inductively coupled plasma—reactive ion etching (ICP-RIE). The depth of etching was approximately 150 nm to separate devices and test structures, so the etching procedure was stopped at the top of the semi-insulating GaN buffer layer. Three different widths of mesa structure (corresponding to the width of EdgeFETs and FinFETs) were tested: 2, 3 and 4 μm. The ohmic contacts Ti/Al (200/1000 Å) were deposited at the next step for the formation of drain and source contacts. Afterward, rapid thermal annealing of ohmic contacts was conducted at 600 °C in a nitrogen atmosphere for 60 s. As the third step, the Schottky contacts consisting of Ni/Au (250/750 Å) were deposited directly on the edges of the mesa in cases of EdgeFETs and also on the top of the mesa for standard FinFETs. Channel length and width defined in this process were equal to 2, 3 or 4 μm. At the last step, all contacts were additionally capped with 2 μm thick electroplated gold for better electrical contact between metal pads and probes. The electroplated gold layer, in the case of its deposition on the top of the ohmic contacts, was preceded by sputtering a layer of Ni/Au (250/750 Å), which provided appropriate gold adhesion. The obtained structures of EdgeFET and FinFET are shown in figure 2.

Experimental results and discussion

Similarly to the most common design of 2DEG FinFETs, our EdgeFET devices consist of two ohmic contacts to the 2DEG channel and two Schottky junctions of lateral gates.

The transfer current-voltage characteristic of EdgeFETs (figure 3) indicate that these devices can be pinched off by two LSB gates by reasonable gate voltage even for the highest gate width used, that is \( W = 4 \mu m \). Threshold voltage of EdgeFETs with \( W = L = 4 \mu m \) was in the range from \(-15 \) V to \(-25 \) V. It should also be noted that in this range of gate voltage \( (V_G) \) the reverse leakage current is extremely low \( (I_G = 10 \text{ nA at } -20 \text{ V}) \), which is an equivalent to the normalized value of \( 5 \mu \text{A mm}^{-1} \). Comparing the EdgeFET and FinFET transfer characteristics (figure 3) one can see that at the low gate voltage \( (V_G = 0–2 \text{ V}) \) the transfer characteristics of FinFETs and EdgeFETs are similar. This effect can be related to the slight covering of the channel by gate metallization due to the minor misalignment of the lithography process.

For understanding the transistor pinch-off process of the EdgeFET channel, we proposed a gradual channel model. The model based on the gradual channel approximation is schematically shown in figure 4. In this case the effective channel width \( W^*(x) \) varies in the \( x \) (source—drain) direction due to a change of depletion region length. Then a simple expression for drain current can be written as

\[
I_D = q\mu N_s W^*(x) \frac{dV}{dx} \tag{1}
\]

where \( q \) is the electron charge, \( \mu \) is the electron mobility of the 2DEG channel, \( N_s \) is the carrier concentration of the 2DEG channel. Taking into account the expression for depletion region length at interface ‘3D-metal/2DEG’ obtained from

![Figure 2. NoMarski contrast microscope photos of GaN/AlGaN EdgeFET (a) and FinFET (b).](image)

![Figure 3. Comparison of EdgeFET and FinFET transfer characteristics.](image)
Figure 4. Gradual model of EdgeFET channel.

Figure 5. Comparison of transport model dependence with experimental results.

[27], the last equation can be rewritten as

\[ I_D = q\mu N_0 \left[ W - \frac{4\varepsilon_0 V_N}{qN_S} \cdot V(x) \right] \frac{dV}{dx} \]  
(2)

where \( V(x) \) is the potential at \( x \) point, \( \varepsilon_0 \) is the vacuum permittivity, \( \varepsilon \) is the semiconductor permittivity, \( V_N \) is the built-in potential at the Schottky/2DEG contact. After variables separation and integration of equation (2) in the limits from 0 to \( L \) the final expression for \( I_D \) can be obtained as

\[ I_D = \frac{q\mu N_0}{L} \left[ W - \frac{4\varepsilon_0 (V_N + V_G)}{qN_S} \right] V_{ds}^* - \frac{2\varepsilon_0 \mu}{L} V_{ds}^{1/2} \]  
(3)

where \( V_{ds}^* \) — the effective source-drain voltage that takes into account voltage drops on the source and drain contacts and also in the 2DEG channel.

After putting parameters of 2DEG \( N_S = 2 \cdot 10^{12} \text{ cm}^{-2} \) and \( \mu = 1000 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1} \) into equation (3), a good agreement of pinch-off voltage was achieved as shown for the EdgeFET with \( W = 2 \mu \text{m}, L = 4 \mu \text{m} \) in figure 5. Thus the simple gradual model of EdgeFET channel is able to describe its closing mechanism. However, it has some disadvantages. First, the model does not account for a reverse leakage current. Second, there is also a bigger discrepancy between the theoretical and experimental curves in the range of \( V_G \) from \(-10 \text{ V}\) to \(-15 \text{ V} \). A possible reason for the latter is a constant 2DEG carrier concentration considered in the gradual model, whereas a decrease of \( N_S \) value was observed near the pinch-off voltage of EdgeFETs [28].

Figure 6(a) shows our first results of room temperature experiments on non-resonant detection in sub-THz (140 GHz) wave range by EdgeFETs in comparison with the detection by FinFETs. All measurements are performed at room temperature, directly on the wafer using probe needles connections. We characterize terahertz detection properties of EdgeFETs using a radiation source based on an IMPATT diode operating at 140 GHz and providing 30 mW of output power. THz radiation is focused on the detector using Teflon lenses and has linear polarization. During the measurements we always choose the polarization direction that maximizes the signal. The THz beam had a Gaussian intensity distribution and it was aligned along the direction perpendicular to the sample surface.

Our devices work in a non-resonant regime at room temperature due to a small damping length (length of plasma waves perturbation), \( l \), compared to the gate length, \( L \). According to [29], the damping length can be obtained as

\[ l = \sqrt{\mu V_0 / \omega}, \]

where \( \mu \) — electron mobility, \( \omega \) — frequency, \( V_0 = V_G - V_{th} \) — voltage swing, \( V_{th} \) — threshold voltage. To estimate \( l \) we take \( V_0 = 0.01 \text{ V} \) thus the detection signal is maximal close to the threshold voltage. Taking into account room temperature values of electron mobility \( \mu = 0.1 \text{ m}^2/(\text{V} \cdot \text{s}) \) and \( \omega = 2\pi \times 140 \approx 880 \text{ rad/s} \), we found \( l \approx 34 \text{ nm} \), which is significantly smaller than the minimal investigated gate length \( L = 2 \mu \text{m} \) in the current work.

According to [29, 30], the photoresponse can be easily extracted from the FET channel conductivity dependence on the gate voltage using the following formula:

\[ \Delta U = \frac{U_0^2}{4} \left( \frac{d \ln(\sigma_{CH})}{dV_G} \right), \]  
(4)

where \( \Delta U \) is the photoresponse, \( \sigma_{CH} \) is the channel conductivity and \( U_0 \) is the amplitude of the radiation induced modulation of the source-to-gate voltage.

The black line in figure 6(b) is calculated using equation (4). As seen from figure 6(b), the shape of the gate voltage dependence of the signal for the FinFET can be well explained in the frame of this model.

In the case of Edge-FET the detected signal dependence of the gate voltage is very different and equation (4) does not describe well the experimental dependence (figure 6(c)). There might be two main reasons for that. First, a significant gate leakage current reduces the signal and changes its shape. Second, the direct detection by the LSB gates may contribute to the signal either decreasing or increasing the overall
response signal. This signal component dominates at forward bias (figure 6(d)) and has the amplitude of the same order of magnitude as the EdgeFET response signal at negative gate voltage.

In the wide range of reverse biasing, applying to both side gates of the EdgeFET, a constant signal was detected, that didn’t agree well with the calculated signal by equation (4) (see figure 6(c)). In general, the discrepancy between the calculated and experimental curves in figure 6(c) can be related to the significantly higher gate leakage current in the case of the EdgeFET at high gate voltage compared to conventional FinFET (see figure 3).

It also should be noted that the carrier concentration in the EdgeFET channel remained independent in a wide range of gate voltages as it was shown in our previous research [28]. The EdgeFET resistance changes mainly due to the decreasing of the channel width (opposite to HEMTs and MOSFETs where the gate voltage changes the carrier concentration in the channel). A new theoretical approach is clearly needed to explain the terahertz detection mechanism in EdgeFETs. However, near to pinch-off voltage EdgeFET photoresponse is transistor-like, which is due to the closing channel effect relying on EdgeFET current nonlinearity at this point.

Conclusions

We have fabricated and investigated the GaN/AlGaN transistors called EdgeFET, with the gates on the sides of 2D electron gas. Control of the side gates allows changing the width of 2D electron gas and the formation of a wire, which should be beneficial for observation of terahertz plasma wave resonances. This paves the way towards future terahertz detectors and emitters using high-quality factor plasma wave resonances, for which it is necessary to eliminate oblique modes.

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