Fabrication of Graphene Field-effect Transistor with Field Controlling Electrodes to improve $f_T$

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1. Introduction

The advantages of Graphene as a channel material of FETs include but not limited to its perfect 2D confinement of carriers, high carrier mobility, mechanical flexibility, extremely high thermal conductivity and long phonon mean free path [1,2]. As Graphene is a zero bandgap material, there is no separation or forbidden states between Graphene's valence band and conduction band. In case of a conventional semiconductor material with nonzero bandgap (e.g. Silicon with a bandgap of 1.1 eV), electrons at the valence band need to gain energy equal to or more than the material bandgap to jump up to conduction band, thus contributing in electrical conduction. For transistors made of these materials, it is possible to cease the electron flow from valence band to conduction band by applying suitable gate bias, thus ceasing the channel current. The negligible current still passing through the channel in this condition is termed as off-state current. This small off-state current makes the on/off current ration of these devices very high which is important for reliable switching in logic devices. In contrast, due to the lack of bandgap in Graphene, electrons in its valence band can easily go to conduction band, thus contributing in conduction, and its cessation is not possible by applying gate bias. There is a non-zero minimum conduction point in Graphene FETs which can be considered as off-state current. However, this off state current is non-negligible, thus makes the device on/off current ratio unacceptably low for switching in logic devices [3]. On the contrary, significant advancement has been made on Graphene devices for analog applications. The access resistance reduces the transconductance and drain current of FET, in general, and its adverse effect on current-gain, as well as, on current-gain cut-off frequency ($f_T$) is well known. That is also true for GFET. To utilize the complete advantage of Graphene as a FET channel material, the set of limitations on the high-frequency performance of GFETs, arisen from the access resistances must be eliminated. Improving high frequency performance by reducing access resistance in III-N HFET and GFET has been already reported [4–6, and]. Two Capacitively coupled and independently biased contacts (Field Controlling Electrode, FCE) at the access region can reduce the access resistance of GFET and increase $f_T$ significantly. If additional bias is applied to the capacitively coupled additional contacts, it induces additional carriers at the access region of the device which effectively reduces the access resistance. The current gain cut-off frequency is inversely proportional to access resistance. Thus by applying additional bias to the additional contacts, the induced additional carriers at the access region effectively increase $f_T$. The $f_T$ improvement of GFETs due to these additional contacts has been estimated from numerical and analytical calculations in [7,8]. Here we have fabricated the novel structure GFET with two additional contacts at the access region, measured its DC characteristics and current-gain, and compared with same geometry conventional GFET without FCEs.

2. Theory

The schematic of a conventional 3-terminal GFET on SiO2 with the small-signal equivalent circuit laid on top is shown in Fig. 1. The time a carrier takes to travel from source to drain, termed as delay time,
can be divided into parts: transit delay, $\tau_{\text{trans}}$ and parasitic delay, $\tau_{\text{par}}$. The transit delay is directly proportional to the intrinsic and extrinsic gate capacitance; whereas, the parasitic delay is proportional to the gate capacitances, as well as, on parasitic resistances. The current gain cut-off frequency $f_T$ is inversely proportional to the total delay time in the device and can be expressed as [9]

$$1/2\pi f_T = \tau_{\text{trans}} + \tau_{\text{par}}$$

As shown in [7,8], the induced carriers caused by FCE modulation effectively reduces the resistance of the ungated access regions and thus results in a decrement of $\tau_{\text{par}}$ and increment of $f_T$.

3. Fabrication

Rather than following the conventional sequence of GFET fabrication steps starting with Graphene transfer and mesa etch, and ending with gate patterning, here we started the process by firstly patterning Gate-FCE on substrate and finished by doing the mesa etch of Graphene, to prevent Graphene from excessive contamination due to exposure to resists, solvents, and developers. The SiO$_2$ substrate was cleaned with acetone/isopropyl alcohol/methanol, rinsed with deionized (DI) water, and dried with N$_2$ flow. 200 nm of 950 PMMA A4 was spin coated and oven baked at 185 °C for 30 min. The Gate-FCE layer with alignment marks were patterned using e-beam lithography and developed in a solution of 1: 3 MIBK: IPA. 10-nm Ti/40-nm Au was evaporated using e-beam evaporator at a chamber pressure of $2 \times 10^{-7}$ mTorr and lifted-off in acetone, in a standard sonic bath. The next layer was the pads for which the patterned substrate was coated with 600 nm LOR 3B/600 nm S1805 photoresist. After UV exposure, it was developed in developer MF-26A for 15 s, rinsed with DI, dried with N$_2$, and a descum was done by oxygen plasma etching for 15 s. 10-nm Ti/500-nm Ni was evaporated for pad layer metallization and lifted-off. Following the Gate-FCE layer and pad layer formation, 20 nm HfO$_2$ was deposited by atomic layer deposition (ALD), as gate dielectric. Then it went through the same photolithographic process with mask to open windows for the pads. The 20 nm dielectric above the pads was etched by reactive ion etching (Chlorine + Argon) through the windows, followed by source/drain patterning. For the source/drain patterning, the same e-beam lithographic process was used and 10-nm Ti/500-nm Au was evaporated, followed by the same lift-off process in sonic bath. Source-Drain pad layer was patterned by the photolithographic process same as that used for Gate-FCE pad layer, followed by a 10-nm Ti/500-nm Au evaporation, and lift-off.

Single layer CVD Graphene grown on Copper sheet was coated with PMMA using a regular spin coating and was put floating on FeCl$_3$ solution for 8 h without any disturbance while copper surface touching the solution. Once the copper was completely etched, it was washed with DI water multiple times without flipping, and eventually was transferred on the patterned substrate. After transfer, the sample was put in a desiccant for 8 h. Graphene covered with PMMA was then
coated with S1805 photoresist and went through the same photolithographic process with mask once again, to open windows for mesa etch, through which oxygen plasma etching was used to etch PMMA and Graphene. Thus we prevented the Graphene from exposure to photore sist and developer. After mesa etch, the sample was put in acetone at 50 °C for 15 min to remove PMMA over the Graphene channel.

4. Result and discussion

The fabricated device had a gate length, \( L_g \approx 2 \mu m \), gate to source/drain access region length, \( L_{acs} \approx 850 \text{ nm} \), FCE length, \( L_{FCE} \approx 270 \text{ nm} \), FCE to gate length, \( L_{FCE-g} \approx 310 \text{ nm} \), and FCE to source/drain length, \( L_{FCE-s/d} \approx 270 \text{ nm} \) as shown in Fig. 2. The device width was 80 \( \mu m \).

Graphene channel was characterized by Raman spectroscopy taken using a 532 nm laser with a spot size of 1 \( \mu m^2 \) As shown in Fig. 3. The 2D/G ratio (0.93) of the Raman spectrum confirms the presence of single layer Graphene.

The DC characteristics of the fabricated device including drain voltage vs. drain current (\( I_D-V_D \)) and gate voltage vs. drain current (\( I_D-V_G \)) was measured using a semiconductor parameter analyzer. The drain current at a constant drain and gate voltage showed strong dependency on FCE bias and showed up to 10.1% increment at \( V_{FCE} = -3.0 \text{ V} \). The \( I_D-V_D \) characteristics of the proposed GFET at \( V_{FCE} = 0 \) is shown in Fig. 5(b). The gate leakage current of the device is plotted in logarithmic scale and shown in Fig. 4(a). The leakage current was at the order of a pA. In addition to gate leakage current, the FCE leakage current was measured as well. The FCE leakage current was at the order of pA as well, as shown in Fig. 4(b).

The RF characteristics of the GFET was measured using a vector network analyzer integrated with a probe station and coplanar waveguide probes. Standard SOLT calibration was performed before measuring the 2-port S-Parameters, which were eventually converted to \( h_{21} \) parameter.

The current gain, \( |h_{21}| \) is plotted with respect to frequency in Fig. 5(b) for two different devices: conventional 3 terminal GFET and the same geometry GFET with proposed additional contacts (FCEs). The DC biasing condition at source, drain and gate were same for both of the devices whereas the proposed device had both of its FCEs biased at \(-3.0 \text{ V}\). From Fig. 5(b), it is evident that \(-3.0 \text{ V}\) applied at both of the FCEs increases the current gain cut-off frequency from 1.10 GHz to 1.22 GHz.

5. Conclusion

In conclusion, we experimentally demonstrated the superior RF performance of a proposed GFET with independently biased additional contacts at the access region, over a conventional GFET. The increment of current gain cut-off frequency was 10.9% and the proposed device could be used for high frequency applications.
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