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Enhanced high-frequency performance of top-gated graphene FETs due to substrate-induced improvements in charge carrier saturation velocity

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Abstract—High-frequency performance of top-gated graphene field-effect transistors (GFETs) depends to a large extent on the saturation velocity of the charge carriers, a velocity limited by inelastic scattering by surface optical phonons from the dielectrics surrounding the channel. In this work, we show that by simply changing the graphene channel surrounding dielectric with a material having higher optical phonon energy, one could improve the transit frequency and maximum frequency of oscillation of GFETs. We fabricated GFETs on conventional SiO₂/Si substrates by adding a thin Al₂O₃ interfacial buffer layer on top of SiO₂/Si substrates, a material with about 30% higher optical phonon energy than that of SiO₂, and compared performance with that of GFETs fabricated without adding the interfacial layer. From S-parameter measurements, a transit frequency and a maximum frequency of oscillation of 43 GHz and 46 GHz, respectively, were obtained for GFETs on Al₂O₃ with 0.5 μm gate length. These values are approximately 30% higher than those for state-of-the-art GFETs of the same gate length on SiO₂. For relating the improvement of GFET high-frequency performance to improvements in the charge carrier saturation velocity, we used standard methods to extract the charge carrier velocity from the channel transit time. A comparison between two sets of GFETs with and without the interfacial Al₂O₃ layer showed that the charge carrier saturation velocity had increased to 2·10⁷ cm/s from 1.5·10⁷ cm/s.

Index Terms—Field-effect transistors, graphene, transit frequency, maximum frequency of oscillation, optical phonons, saturation velocity.

I. INTRODUCTION

Graphene with its high intrinsic charge carrier mobility and velocity [1], [2] has received interest as a channel material for high-frequency field-effect transistors [3]–[6]. Promising transit and maximum oscillation frequencies have been reported for top-gated graphene field-effect transistors (GFETs) yielding competitive frequency times gate length ($f \times L$) figures of

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merit [5], [7], [8]. However, the high frequency performance of GFETs, in particular, the maximum frequency of oscillation (f_{\max}), is limited by the intrinsically high drain conductance (g_d), caused by zero-bandgap in monolayer graphene, and extrinsic factors such as the elastic and inelastic scattering of charge carriers associated with dielectric materials surrounding the graphene channel [6], [9]–[11].

Charge carrier saturation velocity (v_{sat}) of conventional GFETs fabricated on SiO₂/silicon substrates is limited by inelastic scattering of the low energy surface optical phonons of the adjacent dielectrics [12]–[15]. The optical phonon energy ($\hbar\omega_{\text{op}}$) of SiO₂, the commonly used substrate dielectric, is in the range of 50-60 meV, which is much less than the 160-200 meV of graphene and will therefore limit the charge carrier velocity in graphene [13], [16]. GFETs with the graphene channel embedded between a SiO₂ substrate dielectric and Al₂O₃ gate dielectric exhibit a saturation velocity of $1.5 \cdot 10^7$ cm/s [15]. The hexagonal boron nitride (hBN) with optical phonon energy around 100 meV [4] is a promising option, but not yet feasible for wafer scale device manufacturing. A possible option is to completely surround the graphene channel with layers of Al₂O₃, a dielectric with relatively high $\hbar\omega_{\text{op}}=87$ meV [14], for application in high frequency FETs [17], [18].

In this letter, we show the improvements in the saturation velocity and corresponding enhancement in GFET high-frequency performance by measuring GFETs with a thin buffer layer of Al₂O₃ on the SiO₂/Si substrate [18], [19]. We measured the extrinsic transit frequency (f_T) and f_{\max} up to 43 GHz and 46 GHz, respectively, for 0.5 μm channel length, which outperform state-of-the-art GFETs of similar gate lengths. The improvements in the high frequency performance is correlated with a corresponding 30% increase in the v_{sat} , up to $2 \cdot 10^7$ cm/s, in GFET with Al₂O₃ buffer layer.

II. METHODS

A set of GFETs was fabricated using the same design and fabrication process as previously described [18], the only exception being that a 60 nm thick Al₂O₃ layer was added by atomic layer deposition on top of the 1 μm thick thermally grown SiO₂ layer covering the high-resistivity silicon

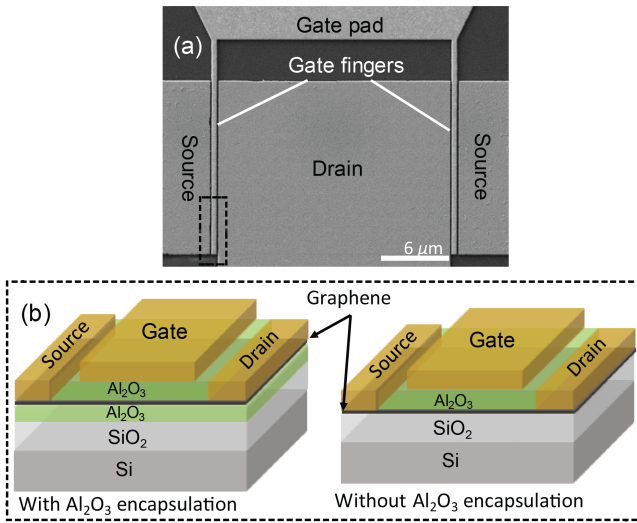


Fig. 1. (a) Top view SEM image of a fabricated two-finger GFET, and (b) cross-sectional schematic views of GFET gate region, corresponding to the dashed box in (a), with and without Al_2O_3 buffer layer. NB! Drawings are not to scale.

substrate. After graphene transfer to the $\text{Al}_2\text{O}_3/\text{SiO}_2/\text{silicon}$ substrate, a 22 nm top gate Al_2O_3 dielectric was deposited leaving the graphene channel interfacing Al_2O_3 both above and below as shown in Fig. 1. Also shown in Fig. 1 is a GFET from the reference set of devices with its graphene channel placed directly on the substrate SiO_2 layer. The gate geometries of the two sets of two-finger GFETs, which we used for comparison, were $0.5 \mu\text{m}$ for the gate length and $2 \times 15 \mu\text{m}$ for the gate width, see an SEM image of the two-finger GFET in Fig. 1.

After fabrication, GFETs from both sets of devices were characterized for extracting their low-field dc-parameters, and for finding the f_T and f_{max} . Fig. 2 shows the drain resistances vs. gate voltage, and the output characteristics (I_D vs. V_D) of two selected GFETs with similar low-field mobility, one from each set, measured at room temperature. Also shown in Fig. 2(b) is the intrinsic output conductance obtained from $g_d = \partial I_D / \partial (V_D - I_D R_C)$ [20], where R_C is the contact resistance and corrected as Chou et al. [21]. By fitting the drain resistance models [22], [23] to the experimental data, we found that the residual charge carrier concentrations (n_0), low-field mobility (μ_0), voltage overdrive ($V_{\text{GS}} - V_{\text{Dirac}}$) and R_C are $12 \times 10^{11} \text{ cm}^{-2}$, $1800 \text{ cm}^2/\text{Vs}$, 20 V , 0.7 V and $20 \times 10^{11} \text{ cm}^{-2}$, $1800 \text{ cm}^2/\text{Vs}$, 10.5 V , 0.8 V in the two selected GFETs with and without Al_2O_3 , respectively.

The GFET S-parameters were measured using an Agilent N5230A VNA and calibrated using standard two-port SOLT calibrations. The S-parameters were used to obtain the small-signal current gain (h_{21}), and the unilateral power gain (U) from which the extrinsic transit frequency f_T and the extrinsic maximum frequency of oscillation f_{max} could be extracted at 0 dB [24], [25]. Some typical plots of the h_{21} vs. frequency, and the transit frequency vs. drain voltage are shown in Fig. 3 for the two selected GFETs. In the analysis below, the charge carrier velocity was extracted directly from intrinsic transit

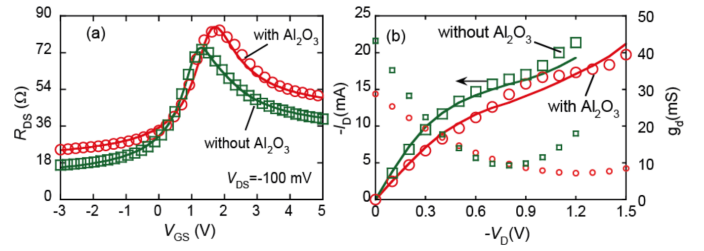


Fig. 2. DC-characteristics of two GFETs with and without Al_2O_3 buffer layer. (a) Drain resistance vs. gate voltage. Solid lines show models [22], [23] fitted to experimental data (symbols). (b) Drain current and intrinsic drain conductance vs. drain voltage. The lines are simulations using the models presented by Meric et al. [4] including the thermally generated charge carriers as in Dorgan et al. [12].

frequency $f_{T,\text{int}} \approx v/2\pi L$, where v is the charge carrier velocity, using delay time analysis [26], [27].

III. RESULTS AND DISCUSSIONS

In this analysis, GFETs from two sets of samples with and without Al_2O_3 buffer layer were characterized and their high frequency performance compared as function of low-field mobility, as shown in Fig. 4(a). The low-field mobility has been chosen as the most appropriate indicator of the graphene quality enabling a fair comparison between the two sets of devices [18]. Despite variations in the obtained data, there is a clear improvement in the transit frequency of GFETs with Al_2O_3 buffer layer as compared to the GFETs with graphene on SiO_2/Si substrate. At low-field mobilities around $2000 \text{ cm}^2/\text{Vs}$, GFETs with Al_2O_3 graphene channel encapsulation show transit frequencies at least 10 GHz higher than GFETs without. A similar behaviour was observed for the maximum frequency of oscillation.

We show below, by applying the delay time analysis, that the improvement in the high performance is related to the increase in the charge carrier velocity. As it can be seen from Fig. 3(b), the GFET with Al_2O_3 buffer layer has a maximum f_T of 43 GHz, while the GFET without the Al_2O_3 buffer layer has f_T up to 34 GHz. Next step is to relate the experimentally measured extrinsic $f_T = 1/(2\pi\tau_{\text{tot}})$, where τ_{tot} is the total delay time, to the intrinsic transit frequency $f_{T,\text{int}} = 1/(2\pi\tau_{\text{int}})$. It can be done applying the analysis of the FET small-signal equivalent circuit pioneered by Tasker and Hughes [28], and later used in [8], [26], [27] as:

$$f_T = \frac{f_{T,\text{int}}}{1 + g_d R_C + \frac{C_{gd} \cdot g_m \cdot R_C}{C_{gs} + C_{gd}} + \frac{C_{pad}}{C_{gs} + C_{gd}}}. \quad (1)$$

In this equation, g_m is the intrinsic transconductance, C_{gs} , C_{gd} and C_{pad} are the gate-source, gate-drain and parasitic gate pad capacitances, respectively, and $R_C = R_S + R_D$ is the sum of the source and drain contact resistances. R_C is obtained from the R_{DS} vs. V_{GS} characteristic. For the GFET gate capacitance we assumed $C_{gs} = WLC_{\text{ox}}/2$. Here, $C_{\text{ox}} = \epsilon_0 \epsilon_{\text{ox}} / t_{\text{ox}} = 3 \text{ mF/m}^2$ where ϵ_0 is the permittivity of free space, ϵ_{ox} is the permittivity and t_{ox} is the thickness of the gate oxide, because of the ambipolarity of the channel at high field, we assume that $C_{gd} = kC_{gs}$, where k used as a fitting parameter. It can be shown that the effects of the capacitance coupling between C_{gs} , C_{gd}

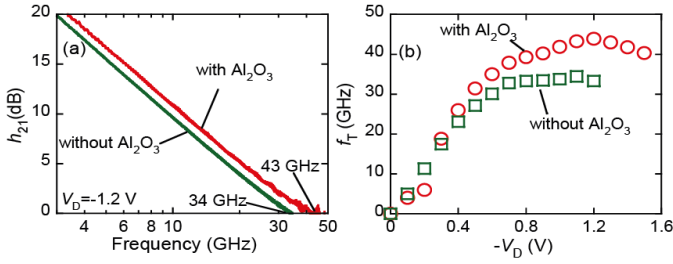


Fig. 3. High frequency performance of GFETs with and without Al_2O_3 buffer layer. (a) Small-signal current gain (h_{21}) vs. frequency. (b) Transit frequency (f_T) vs. drain voltage.

and C_{pad} can be ignored [29]. A gate pad capacitance C_{pad} of 8 fF was obtained as described in Numila *et al.* [26].

From eq. (1), the transit time was easily found by using $\tau_{\text{int}} = (C_{gs} + C_{gd})/g_m$, and the g_d values shown in Fig. 2(b). The g_m obtained here for GFET with Al_2O_3 buffer layer is 16 mA/V compare to 12 mA/V for the GFET without Al_2O_3 interface dielectric. Then, the charge carrier velocity was calculated using the found intrinsic transit time. Fig. 4(b) shows the effective charge carrier velocity versus drain field $E_{\text{int}} = (V_D - R_C I_D)/L$ for the two selected GFETs. In both GFETs the charge carrier velocity saturated at drain fields above 10 kV/cm, which is in good agreement with previous results [12], [15]. Using the Caughey-Thomas velocity model [30], a v_{sat} of $2.0 \cdot 10^7$ cm/s was found for the GFET with Al_2O_3 buffer dielectric, which is approximately 30% higher than the $1.5 \cdot 10^7$ cm/s found for GFETs without Al_2O_3 buffer dielectric. Fig. 4(b) also shows the semi-empirical velocity model (solid lines) fitted to experimental data using γ as a fitting parameter. Also, Fig. 4(b) shows the theoretically estimated saturation velocities using the model by Dorgan *et al.*, assuming that v_{sat} is limited by inelastic emission of optical phonons [12]. These values were calculated using a carrier density obtained from the output characteristic using models [4], [12] at high field for both GFETs with and without Al_2O_3 buffer dielectric.

Combining the analysis of theory and experimental data, one can conclude that charge carrier velocity in the samples with Al_2O_3 buffer interface layer is improved due to the higher optical phonon energy and, partly, due to the lower carriers concentration compared to the sample without Al_2O_3 buffer layer. Our analysis of other devices indicates that this conclusion is valid in the whole studied range of the low-field mobilities. According to our analysis, the GFET without Al_2O_3 buffer layer, in spite of lower saturation velocity, reveal higher drain current (Fig. 2(b)), because of higher intrinsic drain voltage and, partly, because of higher total concentration of the charge carriers.

Finally, as it can be seen from Fig. 5, the highest extrinsic f_{max} for GFETs with and without Al_2O_3 buffer layer were measured to be 46 GHz and 37 GHz, respectively. These values are the highest reported so far for GFETs of similar gate lengths [8]. Fig. 5 shows two dependencies of GFETs with Al_2O_3 buffer layer. The gain of one GFET with Al_2O_3 buffer layer is higher of that without Al_2O_3 buffer layer across whole frequency range. The reduced gain of one GFET at lower

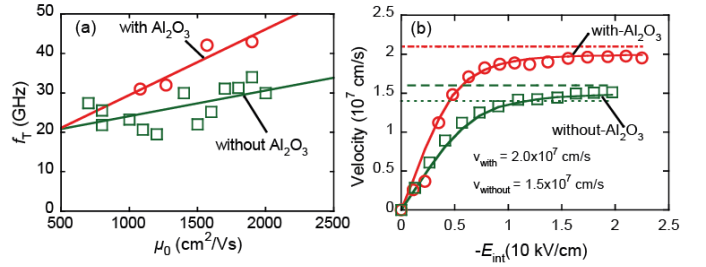


Fig. 4. Effects of Al_2O_3 buffer layer on GFET performance. (a) Transit frequency (f_T) vs. low-field mobility (μ_0) for GFETs with and without Al_2O_3 buffer layer. Solid lines represent linear trendlines. (b) Charge carrier velocity vs. electric field for two GFETs ($\mu_0 = 1800 \text{ cm}^2/\text{Vs}$) with and without Al_2O_3 buffer layer. Solid lines show the Caughey-Thomas model [30] fitted to experimentally extracted data (symbols), while dotted line and dashed lines show the theoretically estimated saturation velocities [12], using $\hbar\omega_{\text{op}} = 60 \text{ meV}$, $n = 24 \times 10^{11} \text{ cm}^{-2}$ and $n = 17 \times 10^{11} \text{ cm}^{-2}$, respectively. Also shown dashed dotted line corresponds to $\hbar\omega_{\text{op}} = 87 \text{ meV}$, $n = 17 \times 10^{11} \text{ cm}^{-2}$. The carrier densities obtained from output characteristics at $E_{\text{int}} = 15 \text{ kV/cm}$.

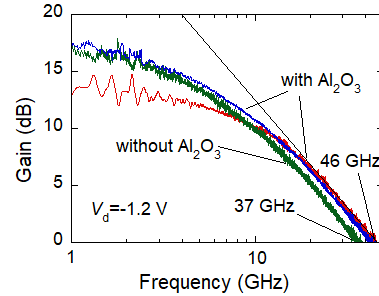


Fig. 5. Maximum frequency of oscillation: unilateral power gain (U) vs. frequency of GFETs with and without Al_2O_3 buffer layer.

frequencies might be attributed to measurement artifact and/or to higher concentration of traps in the gate stack [31]. In terms of scaling, the GFETs in this study have a high $f_{\text{max}} \times L$ figure of merit of $23 \text{ GHz} \cdot \mu\text{m}$, a value comparable to some of the best published MOSFET values [32]. A possible road ahead for further improving GFET high-frequency performance might be to use dielectric materials with even higher optical phonon energies. Preliminary estimates suggest that the v_{sat} in GFETs encapsulated by hBN could be as high as $5 \cdot 10^7$ cm/s corresponding to a $f_{T,\text{int}}$ of 400 GHz at 200 nm channel lengths.

IV. CONCLUSION

In summary, high-frequency top-gated graphene field-effect transistors were fabricated on Al_2O_3 substrate dielectrics, and their performance was compared to that of GFETs on SiO_2 , a dielectric with a lower $\hbar\omega_{\text{op}}$. High extrinsic transit and maximum oscillation frequencies of 43 GHz and 46 GHz, respectively, were obtained experimentally (indicating a figure of merit of $f_{\text{max}} \times L = 23 \text{ GHz} \cdot \mu\text{m}$). The improvement found compared to GFETs on SiO_2 can be explained mainly by the higher optical phonon energy of the encapsulating material resulting in a higher charge carrier saturation velocity. In addition to scaling of the gate length, one road ahead for further progress in high-frequency GFET performance might

be to use the substrate and gate dielectrics with even higher optical phonon energies.

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