GRAPHENE AND 2DM VIRTUAL CONFERENCE & EXPO

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Graphene online 2020 October 19-23

Graphene Field-Effect Transistors Beyond Velocity Saturation

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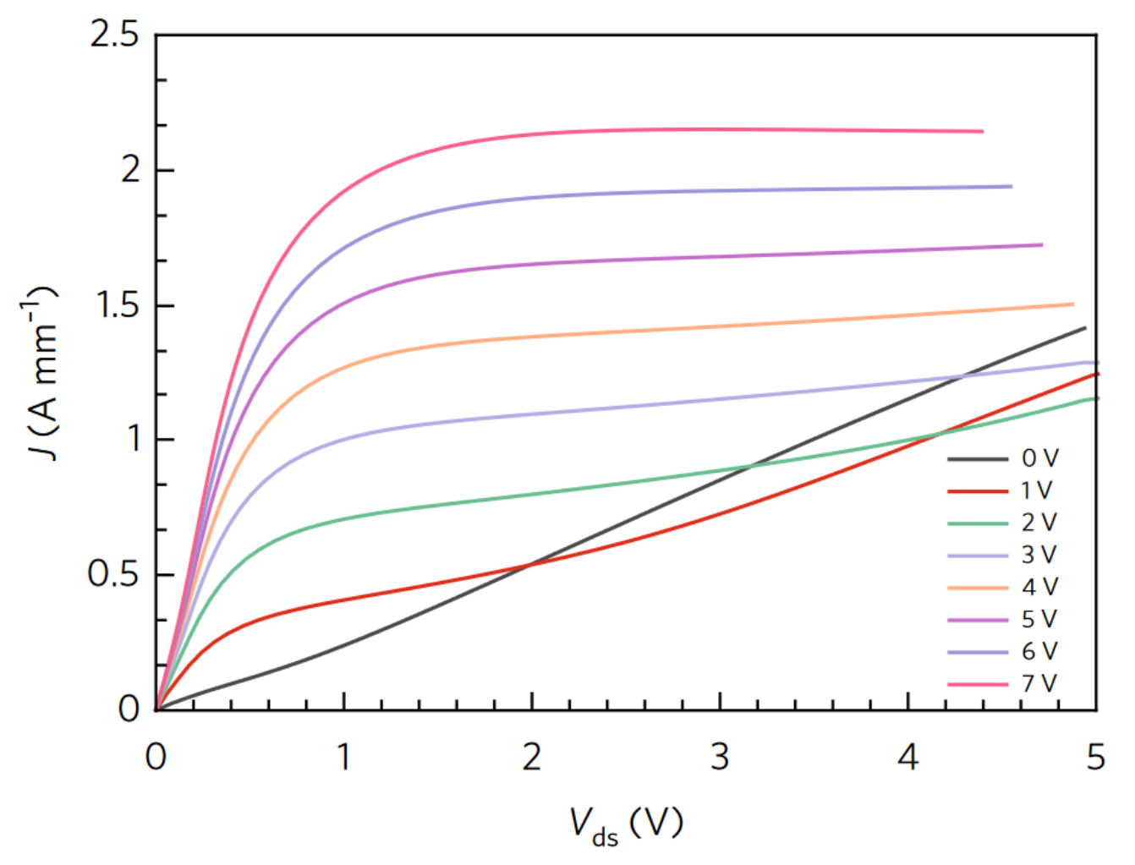
Motivation

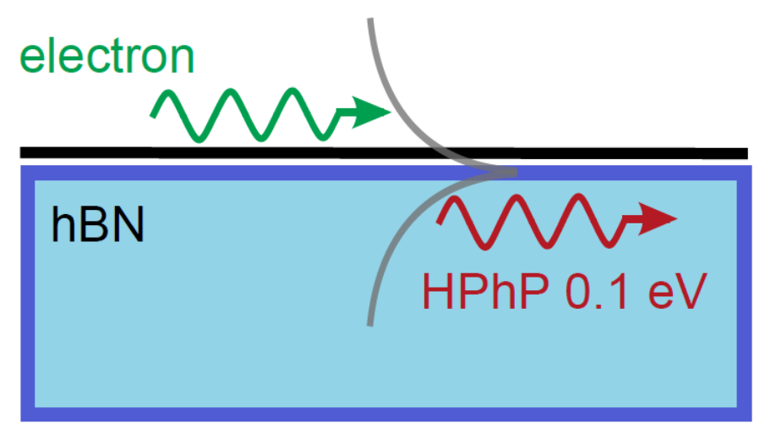
Current saturation is a valuable alternative of bandgap engineering to achieve high-gain graphene field effect transistors (GFETs) for RF applications. One way to face this challenge is to use the hyperbolic phonon polariton scattering mechanism that occurs in graphene supported on boron nitride (hBN) substrate [1].



Current saturation measured for different gate voltages in the electron-doped regime (positive bias). From [1]

Velocity saturation

Saturation velocity is reached on high mobility graphene supported on hBN at large doping when E_F exceeds the optical phonon energy $\hbar\omega_{OP}$. In hBN, this is provided by the lower hyperbolic phonon-polaritons $\hbar\Omega_{I\ HPhP}$ and hot electron cooling by the upper $\hbar\Omega_{II\ HPhP}$ band in the 0.1-0.2 eV range.



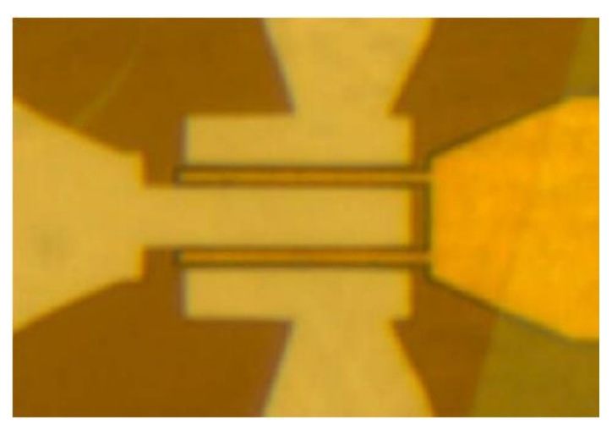
for $E_F \gtrsim \hbar\Omega_I$

$$R = \underbrace{\frac{h\pi}{4e^2 k_F W}}_{\text{Ballistic resistance}} + \overset{\text{Diffusive term}}{\frac{L}{Wne\mu}} + \underbrace{\frac{h\pi}{4e^2 k_F W}\frac{eV_{ds}^0}{\hbar\Omega_I}}_{\text{HPhP scattering contribution}} \Rightarrow$$

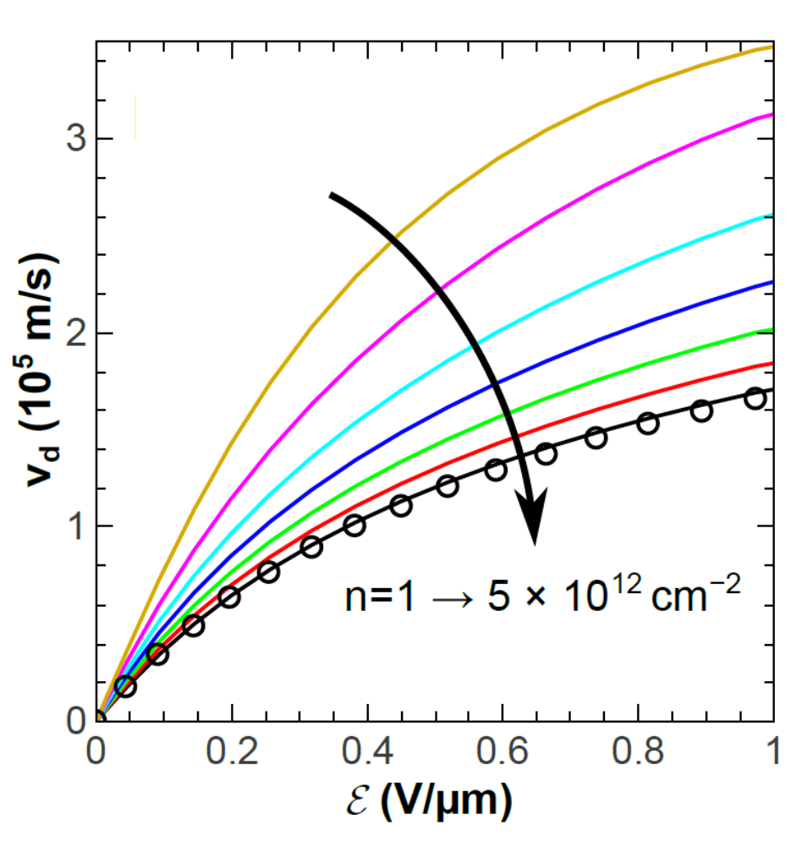
$$\boxed{\begin{aligned} I_{sat} &= \frac{4e^2}{h}\frac{k_F W}{\pi}\frac{\hbar\Omega_I}{e} \\ v_{sat} &\approx \frac{2}{\pi}\frac{\hbar\Omega_I}{E_F} \times v_F \end{aligned}}$$

Intraband DC and RF characterization

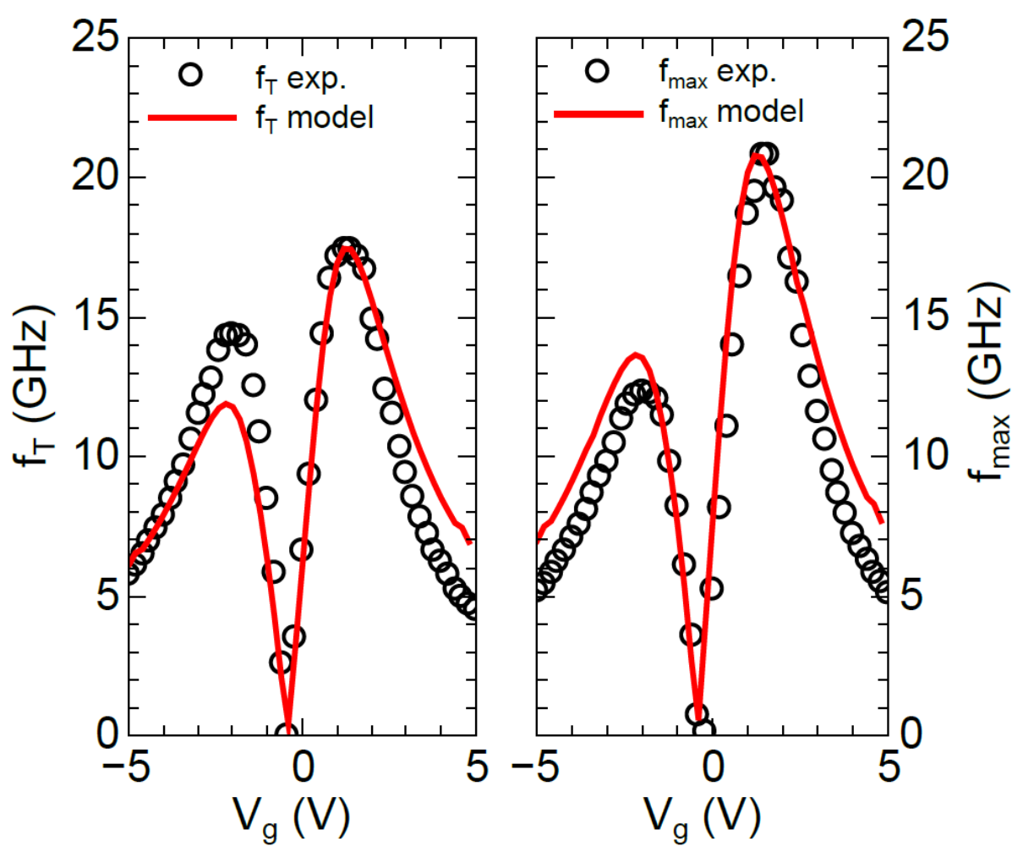
The RF figure of merit increases from $f_{max}/f_T \approx 0.2$ in the mobility-limited regime, over **$f_{max} \approx f_T$ in the velocity-saturation regime** [2].



Optical image of the RF GFET on h-BN with buried bottom gates



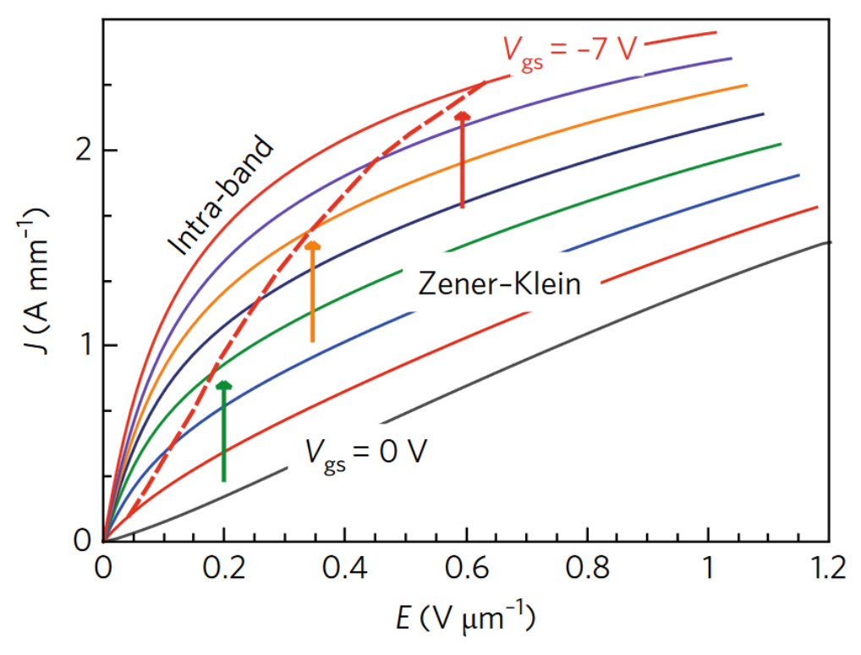
Carrier drift velocity simulated and the measure at n = 5x10^{12} cm^{-2} (black circles).



Cut-off frequencies together with the model prediction. From [2]

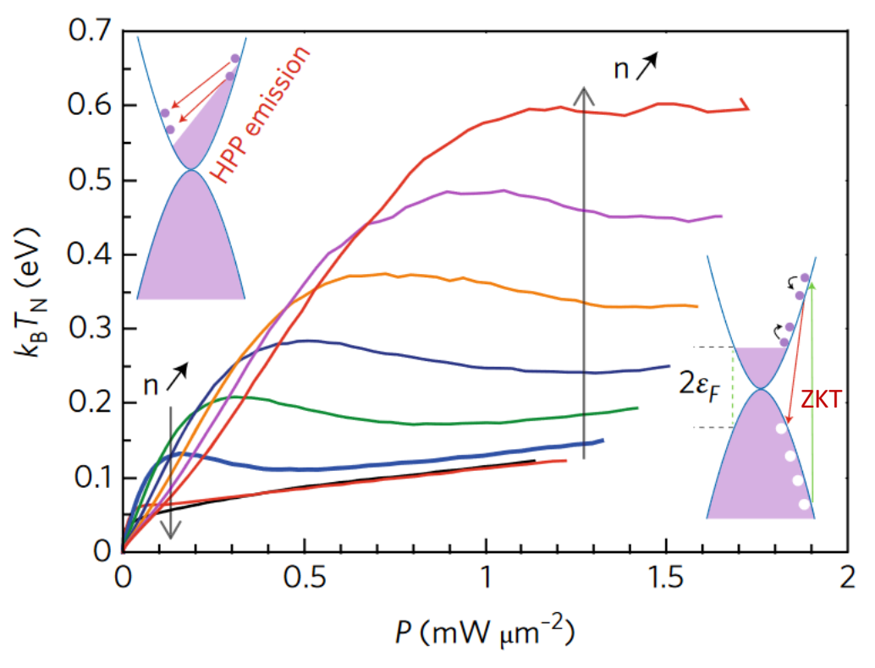
Interband hyperbolic cooling RF GFET

Very-high mobility devices such as hBN encapsulated graphene lead to interband **Zener–Klein tunneling (ZKT) regime** (over $\hbar\Omega_{II\ HPhP}$) [1] with a predicted **$f_{max}/f_T > 5$** [2].



Nonlinear current–field characteristics of the BLG on hBN transistor in the hole-doped ZKT regime.

Radiative cooling by HPhP can also be achieved using thicker h-BN substrates (t_{BN}≥100 nm) [1,3] to overcome self heating limitations [4].



Noise temperature as a function of Joule heating with intraband e$^-$-e$^-$ interactions at low field and interband HPP emission at high field. From [1]

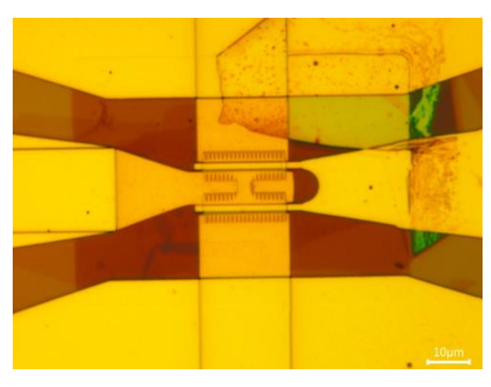
Model taking into account the 3 contribution of current with no self heating :

$$I_{ds} = \underbrace{\boxed{G_{ZKT} V_{ch}}}_{\text{ZKT}} + \underbrace{\frac{V_g}{R_c V_{gc}}\frac{V_{ch}}{1+x}}_{\text{Drude}} - \underbrace{\frac{a}{R_c V_{gc}}\frac{V_{ch}}{1+x}}_{\text{Drain gating}}$$

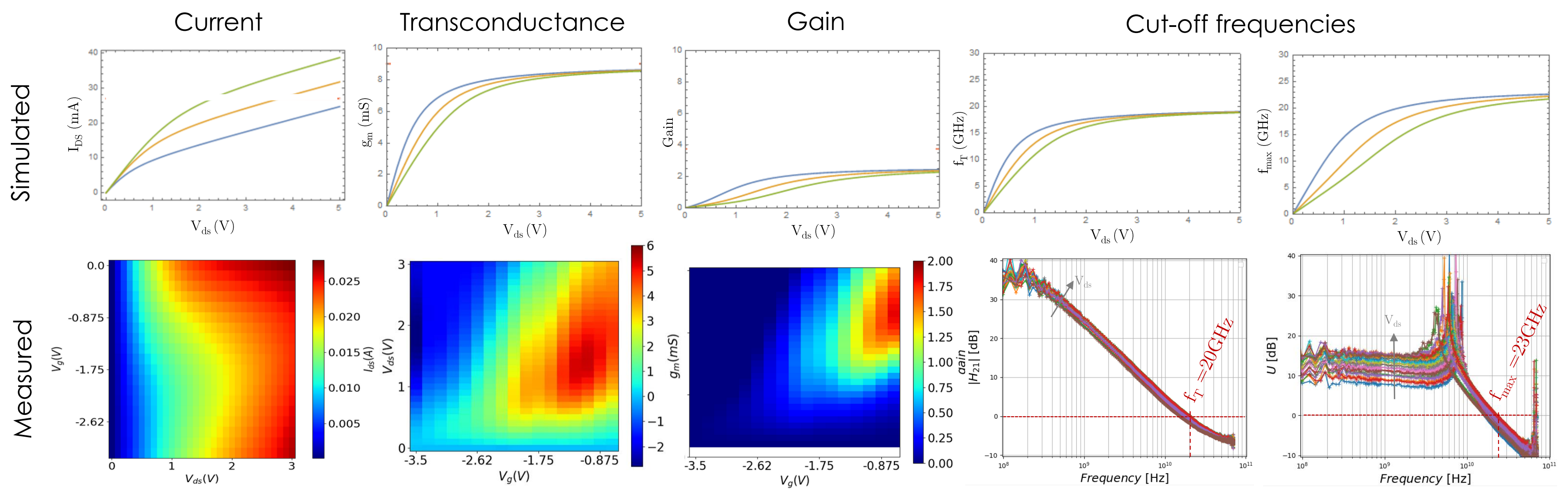
with
$V_{ch} = V_{ds} - R_c I_{ds}$
$x = V_{ch}/V_{sat}$
$V_{sat} = L v_{sat}/\mu$
$(V_{gc} R_c)^{-1} = \frac{W}{L} C_g \mu$
a= drain gating slope

Optimized RF-GFET

A first attempt with high mobility graphene with encapsulated graphene is consistent with the model.

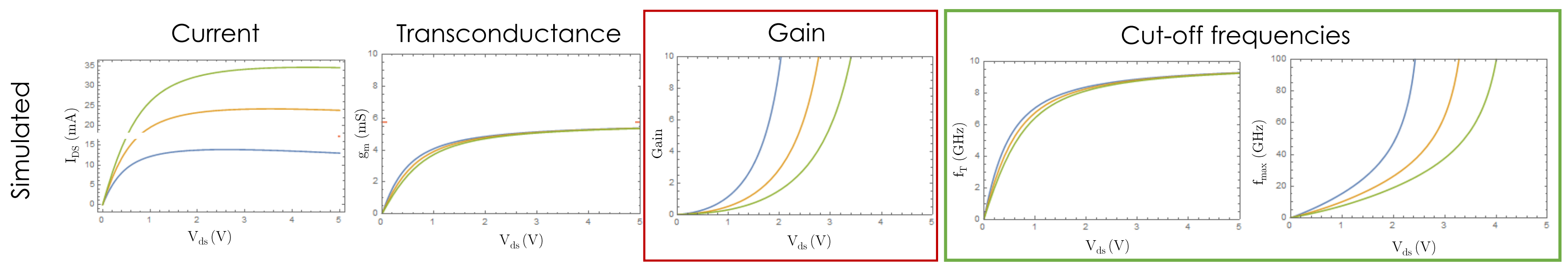


RF hBN encapsulated GFET before design optimization



DC, RF characterization and modelling of a GEFT with μ=3m²/V.s, v_{sat}=2.5 10^5 m/s, L=2μm, W=40 μm, R_c=35 Ω, a=0.2, σ_{zk}=0,3 mS

We anticipate the possibility of $\boldsymbol{f_{max} \geq 100\ \mathrm{GHz}}$ [5] with an optimized design ($L_{ch} > L_{sat}, W_{ch} < W_{contact}$) and operating bias conditions (balance between ZKT and Drain doping) :



Gain tension :
$$A = \frac{G_m}{G_{ds}} \leq \frac{V_{sat}}{(\sigma_{zk}/C_g\mu - 2aV_{sat})} \approx 10$$

Transit frequency:
$$f_T = \frac{G_m}{2\pi C_g LW} = \frac{v_{sat}}{2\pi L} \approx 10\ GHz$$

Maximum oscillation frequency:
$$f_{max} \leq f_T/\sqrt{4R_c G_{ds}} \approx 10 f_T$$

We also envision new perspectives "beyond GFETs", beyond 100GHz using plasma resonance devices [6] highly suitable for RADARs and GSM applications operating in the sub THz domain.

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Graphene online 2020