Impact of Hot Carrier Stress on the Defect Density and Mobility in Double-Gated Graphene Field-Effect Transistors

Yu.Yu. Illarionov*, M. Waltl*, A.D. Smith‡, S. Vaziri‡, M. Ostling‡, M.C. Lemme§ and T. Grasser*

* Institute for Microelectronics, TU Wien, Austria
† Ioffe Physical-Technical Institute, Russia
‡ KTH Royal Institute of Technology, Sweden
§ University of Siegen, Germany

Abstract—We study the impact of hot-carrier degradation (HCD) on the performance of graphene field-effect transistors (GFETs) for different polarities of HC and bias stress. Our results show that the impact of HCD consists in a change of both charged defect density and carrier mobility. At the same time, the mobility degradation agrees with an attractive/repulsive scattering asymmetry and can be understood based on the analysis of the defect density variation.

I. INTRODUCTION

Graphene is a next-generation carbon material with outstanding physical and electrical properties [1, 2] and good compatibility with standard CMOS technology. Although several research groups have succeeded in fabricating graphene-based FETs (GFETs) [3, 4], only a few attempts have been made at trying to understand their reliability [5–7]. All these previous works are devoted to bias-temperature instabilities (BTI) but no analysis has been attempted with respect to hot-carrier degradation (HCD). We thus study the impact of HCD with different polarity of HC and bias components on the defect density and mobility in single-layer double-gated GFETs.

II. DEVICES

Double-gated GFETs with the graphene channel sandwiched between Al2O3 (top gate) and SiO2 (back gate) were fabricated using a standard lithography process [9]. Their layout is given in Fig. 1. Initially, the devices have been treated by baking at $T=300°C$ in an H2/He mixture which resulted in a significant decrease in variability [7]. As shown in our previous works [7, 10], our GFETs share all typical properties known from literature reports [5].

III. EXPERIMENT

We analyze the transformation of the top gate transfer characteristics of GFETs which are known to be sensitive to the detrimental impact of the environment [6]. For this reason, all our measurements were performed in vacuum $(10^{-5}$torr). The impact of HCD and bias stress on the device performance was examined as follows: after measuring the reference transfer characteristic, a stress with constant top gate voltage $V_{TG}$ and drain voltage $V_D$ was applied for a certain stress time $t_s$; the back gate bias $V_{BG}$ was kept at zero. Then the recovery of the stressed device was monitored for several hours after which a new stress with a larger $V_D$ was applied.

Fig. 2 a) Top gate transfer characteristics measured after subsequent stresses ($t_s=10s$) with positive $V_D$ and $V_{TG}-V_D=0$ (pHCD). b) Related results for negative $V_D$ (nHCD). c) Variation of charged trap density shift $\Delta N_T=C_{ox}\Delta V_D/q$ for pHCD and nHCD, the results corresponding to $t_s=10s$ and 100s are plotted. A pHCD stress is able to create only positively charged defects while an nHCD stress creates negatively charged defects at smaller $V_D$ and positively charged ones at larger $V_D$. Interestingly, positively charged defects may tend to disappear after a stress with larger $V_D$, similarly to Si technologies [8].
In the spirit of our previous work [7], $V_{TG} - V_D(V_d) \approx \text{const}$ with $V_D$ being the Dirac voltage was maintained in order to approximately keep the oxide field constant during all stress rounds. Also, in this work all the measurements have been performed at room temperature.

IV. RESULTS AND DISCUSSIONS

In Fig. 2 the resulting transformation of the top gate transfer characteristics after alternating pure HCD ($V_{TG} - V_D = 0$) stresses with increasing positive $V_D$ (pHCD) and negative $V_D$ (nHCD) is depicted. Clearly, the impact of HC stress on the device performance depends on the polarity of $V_D$. pHCD shifts $V_D$ in an NBTI-like manner and also leads to a shape transformation and vertical drift of the transfer characteristics (Fig. 2a). However, nHCD is of PBTI-like nature at smaller $V_d$ and NBTI-like at larger $V_d$ while the transition at moderate $V_d$ is associated with a current increase (Fig. 2b). Then we treat the Dirac point shift in terms of the charged trap density shift $\Delta N_T = C_{ox} \Delta \Delta D_D$ with $C_{ox}$ being the gate oxide capacitance and $\Delta \Delta D_D = V_{fresh} \Delta \Delta D_D$. This allows us to conclude that pHCD leads to a creation of positively charged defects while nHCD introduces a negative charge at smaller $V_d$ and a positive charge at larger $V_d$ (Fig. 2c). An increase of $\Delta T$ makes pHCD more pronounced while in the case of nHCD this leads to a stronger interplay between the two mechanisms. However, under real operation conditions the HC stress occurs in conjunction with the bias stress. Thus we proceed with the analysis of pHCD and nHCD overlaid on either positive (PBTI) or negative (NBTI) bias stress $V_{TG} - V_D = \pm 4 \text{V}$ with the magnitude of the applied HC stress. At smaller $V_d$ a PBTI-like shift of the Dirac point is observed which means that the impact of bias stress dominates. However, at larger $V_d$ an NBTI-like pHCD first reduces the Dirac point shift and then introduces an NBTI-like fast trap shift which is similar to pure NBTI in GFETs [7]. The total $\Delta V_D$ (Fig. 3b) can be separated into strongly recoverable and weakly recoverable components; for convenience each of them is plotted in units of $\Delta N_T$. The strongly recoverable component (Fig. 3c,d) at smaller $V_d$ is mainly associated with bias stress while at larger $V_d$ the strongly recoverable component is suppressed by nHCD but remains PBTI-like due to the presence of larger negative charge density (d), unlike Fig. 3. The weakly recoverable component (e) is similar to the previous case, although an increase of negative charge density obviously proceeds faster. The presence of an extra positive charge at larger stress $V_d$ leads to over-recovery of PBTI-like degradation (b).

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presence of negative charge which is then compensated by pHCD at larger $V_d$. Moreover, an extra positive charge appears after the strong HC stresses which leads to over-recovery of PBTI-like degradation. The related results for PBTI-nHCD are plotted in Fig. 4. A PBTI-like nature of the nHCD component at smaller $V_d$ results in a significant acceleration of the PBTI degradation while its NBTI-like nature at larger $V_d$ leads to its suppression. However, contrary to the previous case, a more significant negative charge density avoids a complete suppression of the PBTI-like behavior. Thus, the strongly recoverable component remains PBTI-like within the whole $V_d$ range and no PBTI-like fast trap appears (Fig. 4c,d). The behavior of the weakly recoverable component (Fig. 4e) is similar to PBTI-pHCD, although an increase of negative charge density obviously proceeds faster.

In particular, an extra positive charge leading to over-recovery of PBTI-like degradation is present at larger $V_d$. In Fig. 5 one can see the results for NBTI-pHCD. Obviously, in this case both the HC and the bias component are able to create only positively charged defects. Thus the degradation is NBTI-like within the whole $V_d$ range and no over-recovery is observed (Fig. 5b).

However, a strong transformation of the shape of the characteristics (Fig. 5a) does not allow to perform a reliable extraction of $\Delta V_D$ for the largest $V_d$. The strongly recoverable component (Fig. 5c,d) initially increases versus $V_d$ and shows the presence of an NBTI-like fast trap shift. But the stresses with larger $V_d$ lead to a decrease of the degradation which indicates that positively charged defects disappear, similarly to Si technologies [8]. The weakly recoverable component (Fig. 5e) behaves versus $V_d$ in the same manner which suggests the absence of any interplay in the considered case.
positive charge results in an incomplete recovery. However, all the degradation mechanisms considered above also lead to a mobility change. The mobility can be estimated using the transconductance \( G_m \), measured in the linear regions of the transfer characteristics [11] (Fig. 7, inset); for unstressed devices \( \mu_e = 90–150 \text{cm}^2/\text{Vs} \) and \( \mu_h = 20–60 \text{cm}^2/\text{Vs} \).

At smaller \( V_d \) the degradation of hole mobility is stronger than for electrons due to the presence of negative charge, leading to an attractive/repulsive scattering asymmetry [12]; screening effects increase the electron mobility at moderate \( V_d \). At the same time, for PBTI-pHCD screening becomes more pronounced after the recovery of the NBTI-like fast traps, since the concentration of positive charge decreases. The inset sketches the mobility estimation procedure.

Since the negative charge concentration for PBTI-pHCD is smaller than for PBTI-nHCD, in the former case the hole mobility is more affected by screening effects. In Fig. 8 the related results for NBTI-pHCD and NBTI-nHCD are provided. In both cases the charge created at smaller \( V_d \) is insufficient for a significant mobility degradation. In the case of NBTI-pHCD, larger \( V_d \) causes a nearly symmetric decrease of the electron and hole mobilities. This suggests scattering at neutral imperfections [12,13] which more likely substitute disappearing positive defects (cf. Fig. 5d,e). The results for NBTI-nHCD demonstrate that at moderate \( V_d \) the electron mobility is affected by screening, similarly to the first two cases. An increase in \( \mu_e/\mu_h \) (inset) also suggests screening while the initial value is close to the one predicted in [12].

V. CONCLUSIONS

The BTI-HCD dynamics for different polarities of HC and bias stress were analyzed. The impact of HCD consists in a variation of defect density and a mobility degradation. These two contributions correlate; knowledge of the charged trap density (sign and magnitude) allows to understand the mobility degradation which is consistent with the previously reported attractive/repulsive scattering asymmetry.

VI. ACKNOWLEDGEMENTS

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