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EFFECT OF HOT-CARRIER STRESS ON THE RECOVERABLE AND PERMANENT COMPONENTS OF NEGATIVE-BIAS TEMPERATURE INSTABILITY

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I. INTRODUCTION AND NOVELTY OF THIS WORK

Although there has been a lot of attention on negative-bias temperature instability (NBTI), because of its impact on P-MOSFET performance, this phenomenon is mostly studied alone, i.e. with the drain grounded or applied with a small voltage for monitoring drain current degradation. In actual circuits, the drain voltage, V_d fluctuates over the entire supply voltage range. Hot-carrier (HC) effect and its possible interaction with NBTI must therefore be properly understood but has not been widely studied[1,2]. In this work, we report the effect of HC stress on the recoverable (R) and permanent (P) components of NBTI. It is shown that HC increases P while it reduces the apparent R under 0-V recovery. Experiments involving a positive gate voltage show, however, that the overall R remains unchanged. This implies that HC tends to increase the density of deep-level hole traps[3]. Evidence from temperature dependence study also reveals coupling of HC and NBTI, especially in the high temperature regime.

II. EXPERIMENTAL DETAILS

Test devices were p^+ polysilicon gate P-MOSFET with gate lengths ranging from 60-120 nm and a fixed width of 10 μm, fabricated by a 65 nm technology. The gate oxide was oxynitride of thickness 1.8 nm, achieved by decoupled plasma nitridation. Devices were stressed under (i) NBTI ($V_g = -2$ V; $V_d \sim 0$) and (ii) HC-NBTI ($V_g = V_d = -2$ V) conditions. Temperature was 100 °C unless stated otherwise. Device degradation was monitored in terms of threshold voltage shift, $|\Delta V_t|$ extracted from linear I_d-V_g curve measured by the pulsed current-voltage method[4,5]. For the HC-NBTI stress, V_d was switched from −2 to −0.1 V before pulsed I_d-V_g measurement was taken with V_g fixed at −2 V. The corresponding V_d switching delay was ~20 ms, but had no consequence on measurement accuracy as the additional degradation arising from HC-NBTI stress was relatively permanent (Fig. 3). Fig. 1 depicts gate and drain waveforms during stress and measurement cycles.

III. RESULTS AND DISCUSSION

A. Effect of HC stress on the Permanent NBTI Component

Evolution of $|\Delta V_t|$ under NBTI (open) and HC-NBTI (filled) stress are compared in Fig. 2. Initial overlap of the two curves signifies that NBTI dominates device degradation at short stress intervals. The effect of HC stress becomes prominent only at longer stress times ($t > 100$ s), as is apparent from the much greater $|\Delta V_t|$ increase as compared to the NBTI case. At a given HC-NBTI stress condition, the more significant increase of $|\Delta V_t|$ in the late stress stage for shorter gate length devices (Fig. 3) confirms the role of HC effect. Fig. 4 shows that $|\Delta V_t|$ remains unchanged for 2×10^4 s following a switch from HC-NBTI to NBTI stress condition. This implies that the additional degradation caused by HC-NBTI stress (arrow A; Fig. 2) is relatively permanent. The ~20 ms delay when V_d is changed from −2 to −0.1 V thus does not affect measurement accuracy as there is negligible recovery of HC-NBTI degradation so long as V_g is kept unchanged at −2 V.

B. Effect of HC Stress on the Recoverable NBTI Component

However, when V_g is switched to 0 V, some recovery can be observed after HC-NBTI (Fig. 5). The effect of HC-NBTI on the recoverable component is examined as follows. A device was first subjected to several NBTI stress and relaxation (0-V) cycles (each lasting 10^3 s). V_d was then changed to −2 V, i.e. HC-NBTI applied for 2×10^4 s before it was set to ~0 V and the NBTI stress and relaxation cycling repeated (Fig. 5). $|\Delta V_t|$ recovery before and after HC-NBTI were compared (Fig. 6). $|\Delta V_t|$ recovery is visibly reduced after HC-NBTI; the decrease is more significant at larger $|V_d|$. Recent studies showed that $|\Delta V_t|$ recovery is mainly due to the detrapping of trapped holes and the broad trap energy distribution (i.e. relatively deep hole traps with energy states above the Si Fermi energy) determines the slow recovery phase[6]. To further examine the reason for the decreased $|\Delta V_t|$ recovery, a positive gate recovery voltage was used and the resultant $|\Delta V_t|$ recovery before and after HC-NBTI were also compared and found to be similar (Fig. 7). This observation implies that HC-NBTI does not affect the total amount of hole trapping but appears to have increased the fraction of deep-level hole traps[3], thus reducing the recovery of $|\Delta V_t|$ under 0-V gate voltage.

C. HC-NBTI Interaction

Fig. 8 depicts the gate length dependence of NBTI and HC-NBTI. For the latter, $|\Delta V_t|$ increases more significantly as gate length is reduced. While a large part of the $|\Delta V_t|$ increase is caused by the increasingly greater HC effect as gate length is reduced (since V_d is fixed), results from temperature dependence study (Fig. 9) suggests that a fraction of the increase stems from the coupling between HC and NBTI. This is apparent from the change in the activation energy of HC-NBTI, from 0.06 eV in the low temperature regime (where lateral heating by V_d predominates and hence the relatively weak temperature dependence) to a much higher value of 0.14 eV in the high temperature regime. The latter is identical to the activation energy of NBTI but the corresponding $|\Delta V_t|$ increase is higher. This implies that lateral heating of channel holes promotes the NBTI effect.

IV. CONCLUSION

HC stressing is shown to significantly increase the P but decrease the R (under 0-V recovery) component of NBTI. The latter results from HC induced trapping of holes at deeper defect levels. Lateral heating of channel holes is found to worsen NBTI degradation, indicating coupling of HC and NBTI effects.

ACKNOWLEDGEMENT

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REFERENCES: [1] Doyle *et al.*, IEDM 1991, pp. 529-532; [2] Guerin *et al.*, IIRW, 2005, pp. 10-16; [3] Ang *et al.*, IEEE TDMR (8), pp. 22-34, 2008; [4] Du *et al.*, IEEE EDL (30), pp. 275-277, 2009; [5] Hu *et al.*, IEEE TED, in press; [6] Ang *et al.*, IEEE EDL (30), pp. 751-753, 2009.

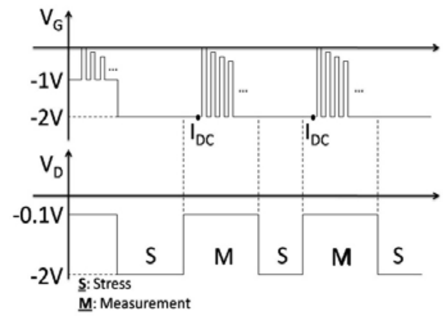

Fig. 1 Gate and drain voltage waveforms during HC-NBTI stress. When measurement is needed, V_d is changed to –0.1 V. Thereafter, it is reset to –2 V to resume HC-NBTI stress.

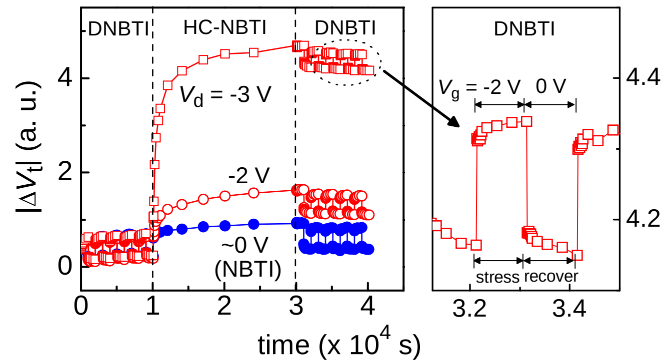

Fig. 5. Five cycles of dynamic NBTI (DNBTI) are first applied to a DUT, followed by HC-NBTI or NBTI for 2×10^4 s. After HC-NBTI, five cycles of DNBTI are resumed. DNBTI conditions – stress: V_g = –2 V, 10^3 s; recovery: V_g = 0 V; 10^3 s. HC-NBTI conditions: V_g = –2 V; varying V_d as shown.

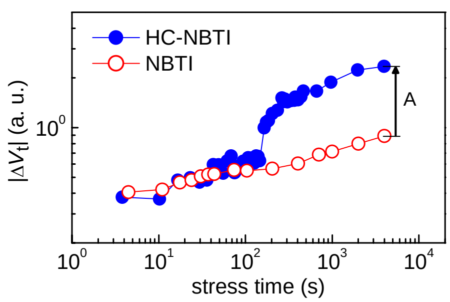

Fig. 2. Evolution of threshold voltage shift, $|\Delta V_t|$ during HC-NBTI and NBTI stress. Increase shift is apparent in the late stage of HC-NBTI.

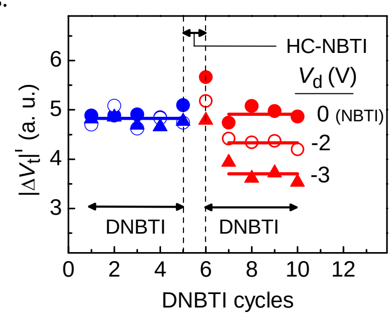

Fig. 6. Comparison of $|\Delta V_t|$ recovery (@ V_g = 0) per cycle before and after HC-NBTI. $|\Delta V_t|$ recovery remains constant without HC-NBTI (V_d = 0). A more severe HC stress effect reduces $|\Delta V_t|$ recovery per cycle.

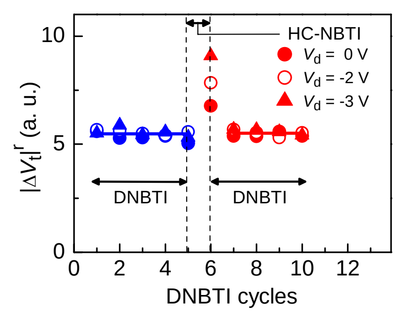

Fig. 7. No difference in $|\Delta V_t|$ recovery per cycle is observed before and after HC-NBTI when a positive gate recovery voltage (+1.5 V) is used.

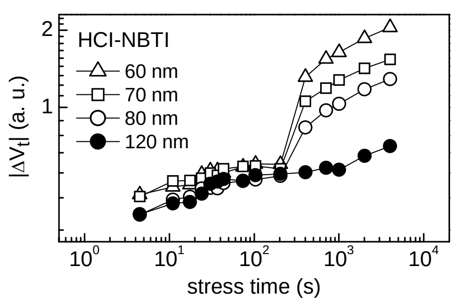

Fig. 3. Evolution of threshold voltage shift, $|\Delta V_t|$ during HC-NBTI stress for devices having different gate lengths.

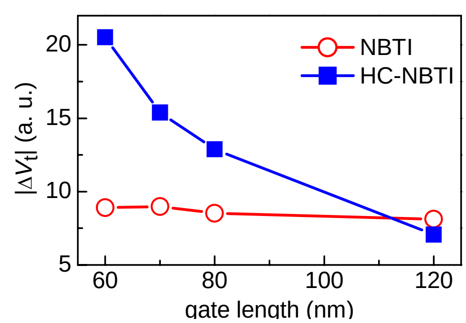

Fig. 8. Gate length dependence of NBTI and HC-NBTI. A much stronger dependence is apparent for the latter. Apart from the expected increase in HC stress severity as gate length decreases (as V_d is fixed)

Temperature dependence study (Fig. 9) shows that HC-NBTI interaction plays a role in the larger roll up for the HC-NBTI.

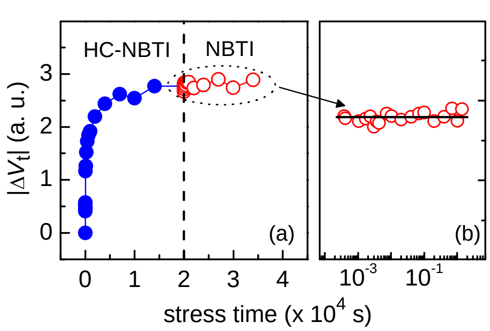

Fig. 4. After switching from HC-NBTI to NBTI stress (i.e. V_d from –2 to ~0 V), threshold voltage shift, $|\Delta V_t|$ remains constant even after a long period, indicating that HC-NBTI induced degradation is relatively permanent.

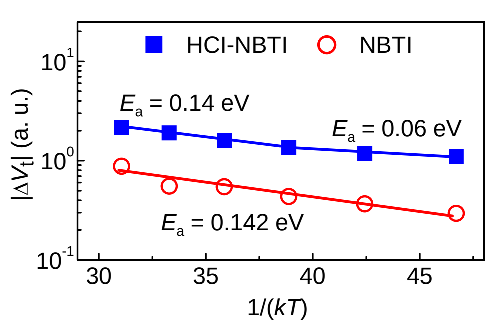

Fig. 9. Arrhenius plot for HC-NBTI and NBTI. For the former, an increase in the activation energy is apparent in the high temperature regime.