Experimental Investigation of NBTI Degradation on Power VDMOS Transistors under Low Magnetic Field

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Abstract- In this paper, we report an experimental evidence of the impact of applied a low magnetic field (*$B<100$* Gauss) during negative bias temperature instability (NBTI) stress and recovery, on commercial power double diffused MOS transistor (*VDMOSFET*). We show that both interface (ΔN_{it}) and oxide trap (ΔN_{ot}) induced by NBTI stress are reduced by applying the magnetic field. This reducing is more pronounced as the magnetic field is high. However, the dynamic of interface trap during stress and recovery phase is not affected by the applied magnetic field. While, the dynamic of oxide trap is affected in both stress and recovery phases.

***Index Terms*— NBTI degradation, Paramagnetic defects, Low magnetic field**

I. INTRODUCTION

It is commonly, accepted that paramagnetic defects are responsible of several instabilities problems in metal-oxide silicon (MOS) devices, such as the Negative Bias Temperature Instability (NBTI) [1-5], which is an important reliability degradation problem affecting the modern CMOS technology [6]. Some authors, have identified the paramagnetic defects induced by NBTI degradation, in silicon MOS transistors, as *Pb center* (at interface *Si/SiO_2*) and *E' center* (in the oxide) [1-5]. However, till now the exact mechanisms behind the NBTI degradation are not well understood and still under debate.

The paramagnetic defects contain an unpaired electron in their orbital which can be sensitive to external applied magnetic field. Indeed, under the influence of the external magnetic field, the unpaired electron in paramagnetic defects orients its spin in a particular direction (spin up or spin down). Under this condition, only the electron with opposite spin can be trapped into these paramagnetic defects. Hence with applied external magnetic field, we can control the orientation of unpaired electron and consequently the spin dependent recombination, trapping and tunneling into the defects. In addition, some authors reported that the applied magnetic field could affect some reactions at *Si/SiO_2* interface [7]. However, we should note that there is only very limited experimental study of magnetic field effect on the creation and behaviors of paramagnetic defects in MOS devices [8-10] .

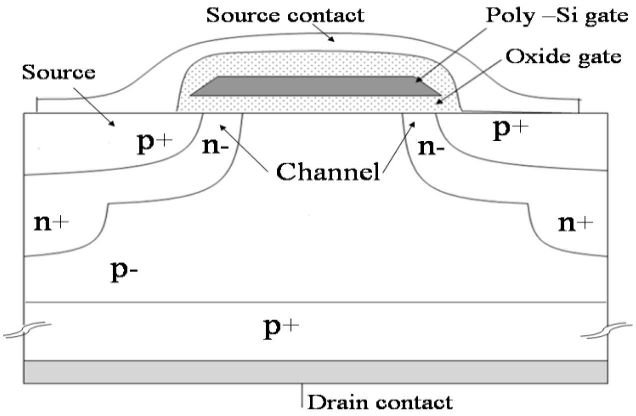

Fig. 1. Cross section of p-channel power VDMOS transistor.

In this paper, we deeply investigate both NBTI stress and recovery on power VDMOSFET transistors under low magnetic field, using many characterization techniques such as charge pumping (CP), drain current measurement and direct-current current voltage (DC-IV). All the three techniques converge toward the same results; the NBTI stress is reduced by applying an external magnetic field.

II. DEVICES AND EXPERIMENTAL SETUP

The devices investigated in this work are commercials p-channel VDMOSFETs *IRF 9530 N* encapsulated in TO-220 plastic cases, with nominal drain current of 14 A, and drain-to source breakdown voltage of 100 V[11]. The device's gate oxide thickness is around of 100nm. We note that, this value is estimated using the capacitance voltage (C-V) and the optical microscope characterization as described in [12]. The initial threshold voltage value of virgin devices was approximately $V_{th}\approx-3.6$V. The cross section of two half-cells of p-channel VDMOSFET is presented on Fig. 1.

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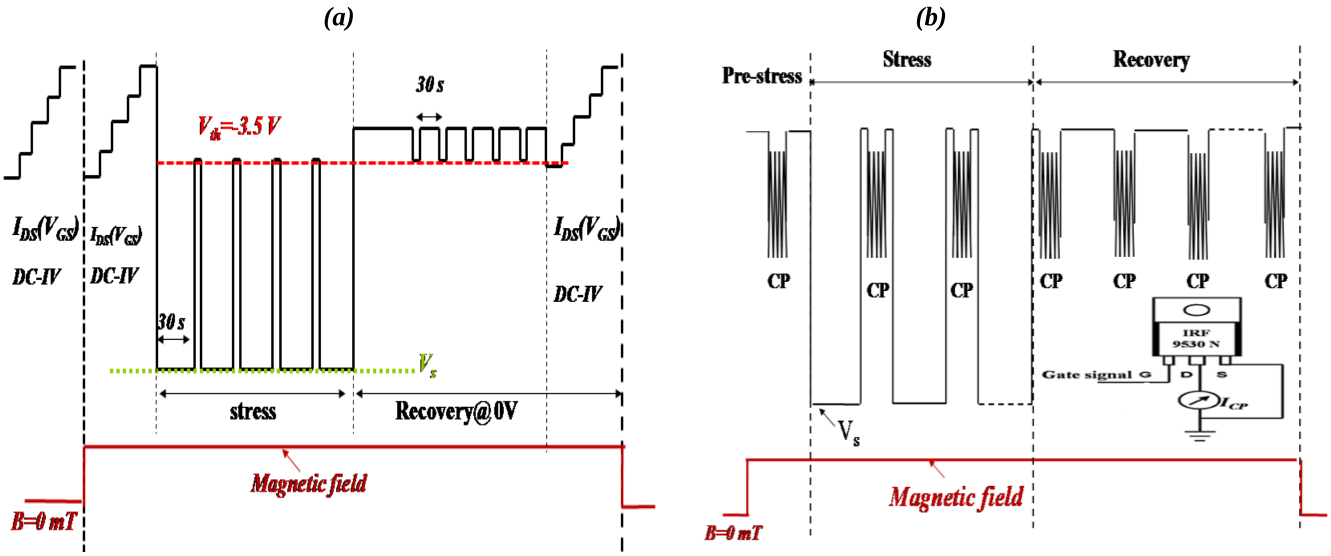

Fig .2 Measurement/stress/measurement (*MSM*) protocols, a) Drain current measurement, b) charge pumping technique

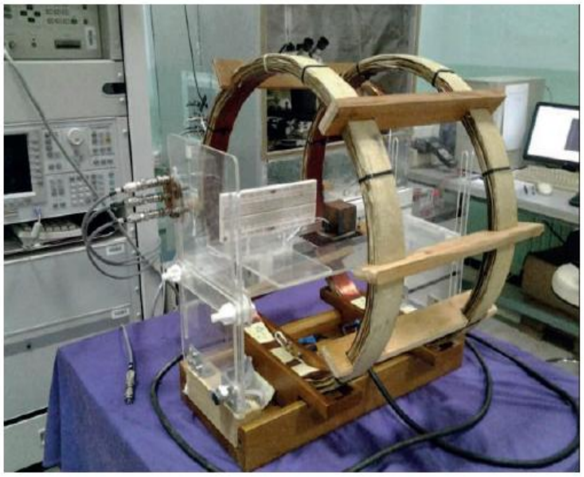

Fig.3 Photo of the Helmholtz coil used to generate uniform magnetic field.

The NBTI stress is performed using two measurement/stress/measurement (MSM) protocols, see fig.2. During the first MSM protocol, the drain current I_{DS} is monitored around V_{th} (at V_G=-3V) with applied drain-source voltage (V_{DS}) of -50 mV. Well during the second protocol the maximum charge pumping current (I_{CPmax}) is measured at the drain contact, with the source grounded. The CP measurements are performed using triangular wave with amplitude of 4 V and frequency of 400 kHz. We have used the triangular wave to reduce the geometric component, while the square wave form with small transition times could increase the geometric component.

MSM protocols are carrying out using the fully automated experimental setup. This includes a sensitive Agilent HP 4156 C for current measurement and Agilent 16440A SMU/pulse generator selector to switch between stress and measurement. The devices are stressed up to 900s by applying a negative voltage of Vs= –60 V, followed by the recovery at zero voltage (V_G=0). The stress temperature is 80°C.

The direct-current current voltage (DC-IV) characteristics are measured before and after stress (with and without applied magnetic field).

The applied uniform magnetic field is generated using in house developed Helmholtz coil with a diameter of 44 cm, which is able to generate a maximum magnetic field of 10 mT, see fig.3. The generated magnetic field is controlled using high voltage computer controlled power supply. Magnetic fields up to 10mT are applied during stress and recovery phases, see fig. 2. The applied magnetic field is perpendicular to the Si/SiO_2 interface.

III. EXPERIMENTAL RESULTS

Fig.4 presents the $I_{DS}(V_{GS})$ characteristics and CP curves (inset the figure) of virgin VDMOSFETs (*IRF 9530 N)* without and with different applied magnetic fields. This figure shows that, all CP curves ($I_{DS}(V_{GS})$ characteristics) with and without magnetic fields are the same. Therefore, there is no magnetic field effect on the drain I_{DS} and CP currents. Consequently, all divergence of NBTI stress induced variation on I_{DS} or CP current $\Delta I_{DS(CP)}$ ($\Delta I_{DS(CP)}$ =$I_{DS(CP)}$ -$I_{DS(CP)0}$, where $I_{DS(CP)}$ and $I_{DS(CP)0}$ are the actual stressed and the initial I_{DS} (CP) current, respectively) with applied magnetic field from that without magnetic field is due to the impact of magnetic field on NBTI stress.

Fig.5(a) compares the threshold voltage shift ΔV_{th} induced by NBTI stress with and without applied magnetic field. ΔV_{th} is clearly decreasing with increasing magnetic fields. The decreasing is important as the applied magnetic field is high.

The same behaviors are observed for ΔI_{CP}, see fig .5(b).

ΔI_{CP} slightly increases during the recovery phases. Note that, the same results (increase of ΔI_{CP} due to the generation of

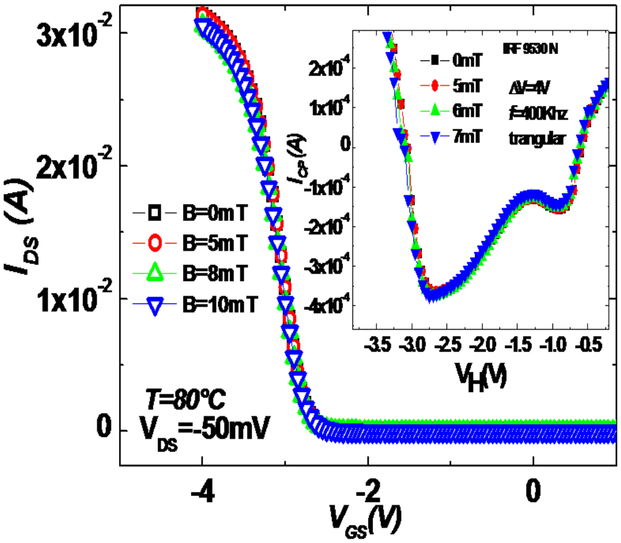

Fig.4 $I_{DS}(V_{GS})$ characteristics and CP curves (inside the figure) of virgin VDMOSFETs

interface trap during the recovery phases) have been reported by Stojadinovic *et al.*[13] and Manic *et al*[14] for a thick gate oxide devices. They have explain this increase by trap redistribution within the silicon bandgap and hydrogen-related reacting species required for both passivation and depassivation processes occurring at the SiO_2/Si interface during the stress and after the end of stress in similar manner as in the case of devices exposed to irradiation [15-17].

All our tested devices at different stress voltage and temperature present the impact of magnetic field (note all show here). In addition, we note that the reducing of the NBTI stress is previously reported in [8-9]. This issue is confirmed and deeply investigated, in this work, using another reference of VDMOSFET which is *IRF 9530 N*.

It is generally, accepted that ΔV_{th} is due to the contribution of both interface and oxide traps [18-20]. However, ΔI_{CP} is dominated by the contribution of interface traps (for high frequency measurements)[21]. Therefore, regarding the above observations, it is clear that both interface traps ΔN_{it} (responsible of ΔI_{CP}) and oxide traps ΔN_{ot} induced by NBTI stress are reduced by applied magnetic field. Thus is confirmed by the comparison of the measured DC-IV characteristics before and after stress with and without applied magnetic fields, this comparison is given in fig.6. The maximum peak, which is related to ΔN_{it}, decreases with increasing magnetic field and the voltage position of the maximum peak, which is correlated to ΔN_{ot}, shift toward the positive voltage with applied magnetic field. That means that, both ΔN_{it} and ΔN_{ot} decrease with increasing of applied magnetic field.

The fig.7(a) compares the normalized ΔV_{th} with and without applied magnetic (ΔV_{th} is normalized to its maximum value in stress phase). The dynamic of ΔV_{th} in both stress and recovery (see inset fig.6.a) phases are affected by applied magnetic field. The dynamic of ΔV_{th} in the stress phase is reduced and the recovery of ΔV_{th} becomes more pronounced (accelerated) as the magnetic field goes high (see inset fig.6.a).

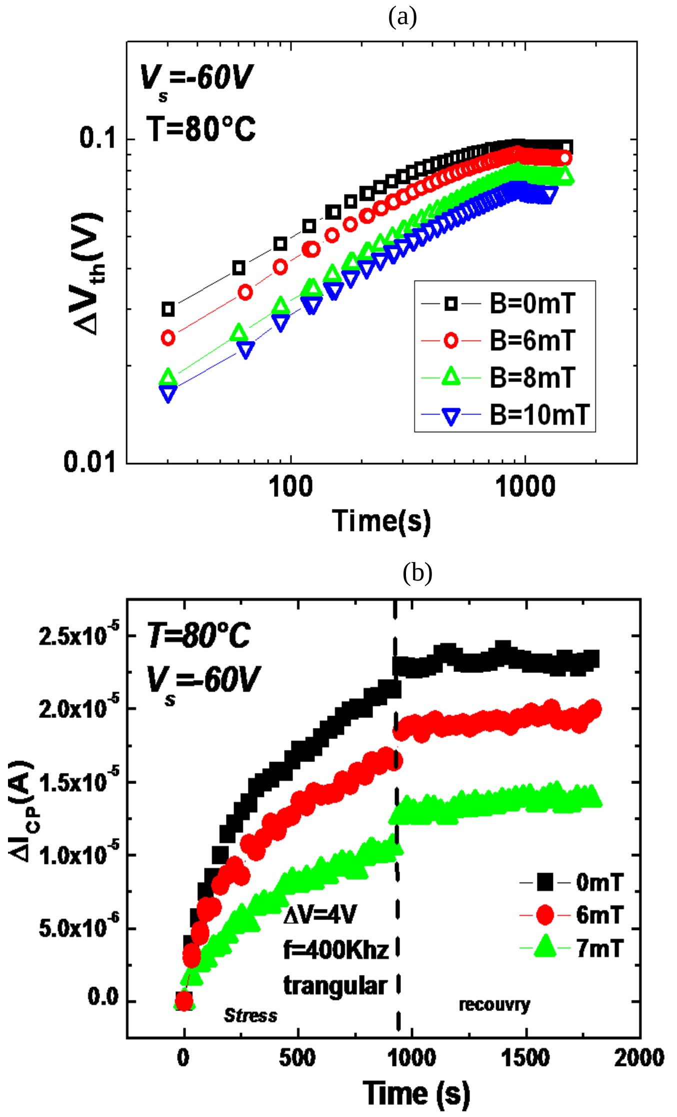

Fig.5 Comparison between threshold voltage shift ΔV_{th} (a) and ΔI_{CP} (b) with and without applied magnetic field.

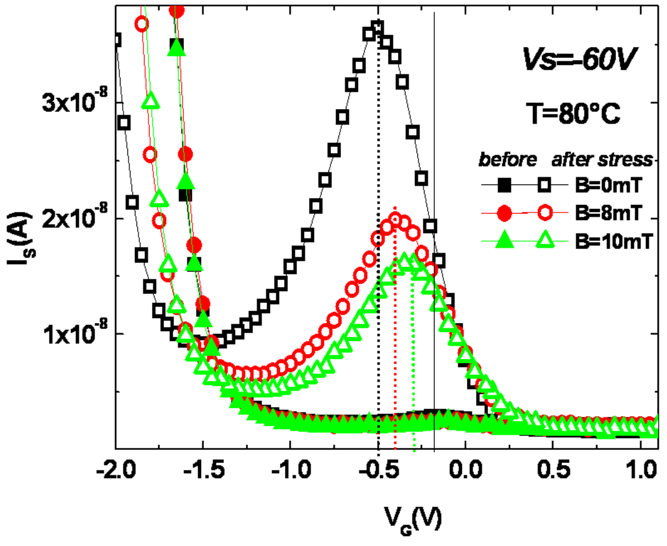

Fig.6 DC-IV characteristics before and after stress with and without applied magnetic field

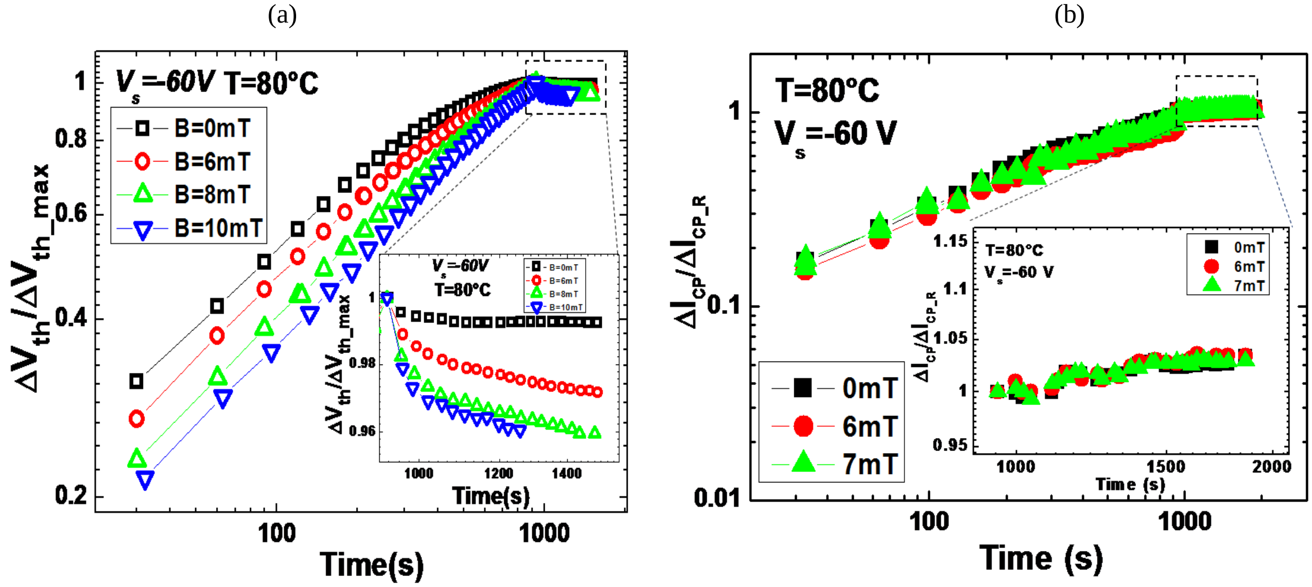

Fig.7 Comparison between dynamic of stress and recovery with and without magnetic field (a) normalized ΔV_{th} (b) normalized ΔI_{CP}. ΔV_{th_max} is the maximum of threshold voltage shift during the stress phase and ΔI_{CP_R} is the first CP current during recovery phase.

However the dynamic of stress and recovery of ΔI_{CP} (related to ΔN_{it}) is not affected by applied magnetic field, see fig.7 (b) and inset this figure. All normalized ΔI_{CP} (to its first value in recovery phase) are the same for both with and without applied magnetic field. According to the above observation, we could conclude that the dynamic of ΔN_{it} is not affected by applied magnetic field in both stress and recovery phases. While, the magnetic field reduced the dynamic of ΔN_{ot} creation and accelerates their recovery. Thus probably explains the decrease of the normalized ΔV_{th} in both stress and recovery phases with increasing of magnetic field, see fig.6 (a).

IV. DISCUSSION

One would expect that the observed impact of magnetic field on NBTI stress is might due to materials used in power devices that sometimes exhibit a magnetoresistance (change in resistance due to the magnetic field) or ferromagnetic effect. However, this not possible since both $I_{DS}(V_{GS})$ characteristics and CP curves of virgin transistors show no change with applied magnetic field.

Since the NBTI induced-interface and -oxide traps are reduced by applied magnetic field, thus is showed by the three used techniques, one can assume that the activation energy of defect formation is increased by applying the magnetic field. However, this is not reasonable due to the fact that the energy imposed by the applied magnetic fields is too small to modify (increase) the activation energy required to create a defect by NBTI. Indeed, for the magnetic field with magnitude of B <10 mT (such as used in this work) the calculated energy is $E_M<1.16\times10^{-6}$ eV, ($E_M=g_e\mu_B B$, where B is the magnetic field, g_e=2.0023193 is the Lande'g-factor and μ_B=5,788×10^{-5} is *Bohr* magnetron) which was four orders of magnitude less than the stress thermal energy at T = 80 °C (30 meV). So, in such a situation, the magnetic field cannot affect the equilibrium state of the defect. Consequently, the impact of magnetic field on NBTI observed in this work, could be arise from the spin-dependent nature of paramagnetic defects induced by NBTI stress, such as spin dependent trapping and tunneling. In fact, the spin dependence trapping and tunneling arise due to the fact that the trapping is only possible if the spin of trapped electron and the unpaired electrons of paramagnetic defect satisfied the Pauli Exclusion Principle (PEP) which stipulates that the electrons cannot be at the same location (same energy state) in the same quantum state [22].

Application of a magnetic field allows the orientation (polarization) of the unpaired electrons of paramagnetic defects and free electrons of the conduction band. Thus reduces the trapping of electrons by PEP. Therefore, the interface and -oxide traps generated by the stress become electrically inactive under magnetic field (we say that they are electrically transparent). This probably way the ΔI_{CP} and ΔV_{th} are reduced by applying magnetic field.

The current corresponding to the above cited mechanisms (spin dependent magnetic field mechanisms) is, generally, very small and it is difficult to study these spin dependent mechanisms effects in a small device area. This is way, we used the VDMOSFET which has an area of 8 mm^2 and contains 17621 VDMOSFET cells. Note that the cells numbers are estimated using the method described in [11].

In addition to the spin dependent mechanisms effects, the electrochemical reaction that leads to the creation and recovery of traps could be influenced by the applied magnetic field. Thus probably could explain, the modification of the creation and recovery dynamics of ΔN_{ot}. We note that many authors report the influence of magnetic fields on rate of the chemical reaction [7, 23]. However, in this work it is hard to determine the nature of the chemical reaction implicated in the reported observation and the impact of magnetic field effect on this reaction. Therefore more investigation is needed;

V. CONCLUSION

In this study, the NBTI degradation of commercial power VDMOSFET under magnetic field is investigated using the charge pumping technique, drain current measurement and direct-current current voltage technique. All used techniques show the same results: both stress and recovery phases are affected by the magnetic field. The physical mechanisms responsible for these behaviors are unclear and are speculated due to the spin dependent mechanisms and the effect of magnetic field on electrochemical reaction that leads to the traps creation and recovery.

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