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Energy Distribution of Positive Charges in $\text{Al}_2\text{O}_3/\text{GeO}_2/\text{Ge}$ pMOSFETs

Jigang Ma, Jian F. Zhang, Zhigang Ji, Brahim Benbakhti, Wei Zhang, Jerome Mitard, Ben Kaczer, Guido Groeseneken, Steve Hall, John Robertson, and Paul Chalker

Abstract—The high hole mobility of Ge makes it a strong candidate for end of roadmap pMOSFETs and low interface states have been achieved for the $\text{Al}_2\text{O}_3/\text{GeO}_2/\text{Ge}$ gate-stack. This structure, however, suffers from significant negative bias temperature instability (NBTI), dominated by positive charge (PC) in $\text{Al}_2\text{O}_3/\text{GeO}_2$. An in-depth understanding of the PCs will assist in the minimization of NBTI and the defect energy distribution will provide valuable information. The energy distribution also provides the effective charge density at a given surface potential, a key parameter required for simulating the impact of NBTI on device and circuit performance. For the first time, this letter reports the energy distribution of the PC in $\text{Al}_2\text{O}_3/\text{GeO}_2$ on Ge. It is found that the energy density of the PC has a clear peak near Ge E_c at the interface and a relatively low level between E_c and E_v . Below E_v at the interface, it increases rapidly and screens 20% of the V_g rise.

Index Terms—Positive charges, energy distribution, $\text{Al}_2\text{O}_3/\text{GeO}_2$, Ge pMOSFETs, NBTI, aging, reliability.

I. INTRODUCTION

GERMANIUM has attracted much attention for end of roadmap CMOS application, especially the pMOSFET because of its high hole mobility [1]–[5]. Ge MOSFETs used to suffer from the lack of a good native oxide and a high level of interface states, but significant progress has been made recently [1]–[5]. It has been reported that the interface state density at the GeO_2/Ge interface can be comparable with that at SiO_2/Si , if the interaction between GeO_2 and Ge and GeO evaporation can be controlled [3], [4]. Al_2O_3 has been used to effectively suppress the GeO evaporation and Ge MOSFETs with promising performance have been demonstrated with an $\text{Al}_2\text{O}_3/\text{GeO}_2$ gate stack [3], [4].

After achieving good initial performance, attention should be paid to its reliability. The lifetime of Si pMOSFETs

is limited by negative bias temperature instability (NBTI) [6]–[11] and the Ge pMOSFET with $\text{Al}_2\text{O}_3/\text{GeO}_2$ also suffers from substantial NBTI. NBTI has two sources: generated interface states and positive charges formed in the gate dielectric by hole trapping, referred to as positive charge ('PC') hereafter [6], [7], [9]. The PCs in Si MOSFETs have a complex behavior and caused much confusion since 1970s [6], [12]–[15]. There is little information on the PCs in $\text{Al}_2\text{O}_3/\text{GeO}_2/\text{Ge}$ and to assist understanding, it is desirable to know their energy distribution. This distribution also provides the PC density at a given surface potential needed for simulating the NBTI impact on devices and circuits.

The objective of this letter is to report the energy distribution of PCs in the $\text{Al}_2\text{O}_3/\text{GeO}_2/\text{Ge}$ system. We have recently developed a technique that can probe the energy distribution of PCs for Si MOSFETs [16] and it is adapted here for Ge MOSFETs. The results show that the energy density of PCs has a clear peak near the Ge E_c at the interface and is substantially lower between E_c and E_v . Once below E_v at the interface, however, it rises rapidly.

II. DEVICE AND EXPERIMENTS

A 700 nm Ge layer was prepared on a Si wafer, followed by oxidation at 150 °C in atomic oxygen to form 1.2 nm of GeO_2 . A 4 nm Al_2O_3 layer was then deposited and the SiO_2 equivalent oxide thickness is 2.35 nm. After the gate metallization with a 10 nm PVD TiN layer, the pMOSFETs were annealed in forming gas at 350 °C for 20 min. The channel length and width is 1 μm and 50 μm , respectively.

The test started with recording the reference I_s – V_g at $V_d = -100$ mV from a gate pulse edge of 5 μs and trapping during this measurement is negligible [17], [18]. The reference threshold voltage, i.e. V_{th0} , was extracted by extrapolating from the maximum transconductance.

After stressing and charging at V_{gst} , $|V_g|$ was reduced from $|V_{gst}|$ to a base level of $|V_{d\text{ischarge},1}|$ for discharge by using the waveform in Fig. 1(a). During discharge, the device was pulsed from $|V_{d\text{ischarge},1}|$ to monitor the V_{th} shift, i.e. ΔV_{th} , at a constant $I_s = 100 \times W/L$ nA. Once Discharge,1 completes, V_g was stepped to $|V_{d\text{ischarge},2}|$ and the same procedure was applied. This allows the extraction of oxide charges as a function of the base discharge voltage. A pulse edge time of 5 μs was fast enough to freeze discharging [19]. The effective density of positive charges, ΔN_{ox} , defined in section III, versus discharging time is given in Fig. 1(b). Fig. 1(b) shows that the discharge mainly occurs within 1 sec, so that a discharge time of 1 sec will be used for each $V_{d\text{ischarge}}$ hereafter. Fig. 1(c) gives the ΔV_{th} at 1 sec of discharge versus $V_{d\text{ischarge}}$. The variation of ΔV_{th} with $V_{d\text{ischarge}}$ is significant.

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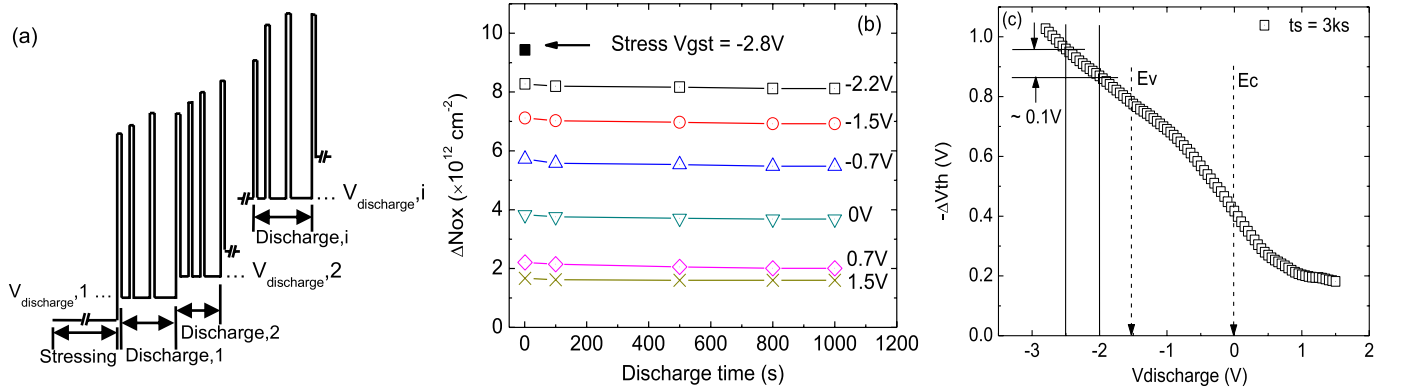


Fig. 1. (a) The V_g waveform; (b) The discharging against time under each $V_{\text{discharge}}$; and (c) The ΔV_{th} at the end of each discharge period against $V_{\text{discharge}}$. The device was stressed at $V_{\text{gst}} = -2.8$ V, 20°C , for 3000 sec.

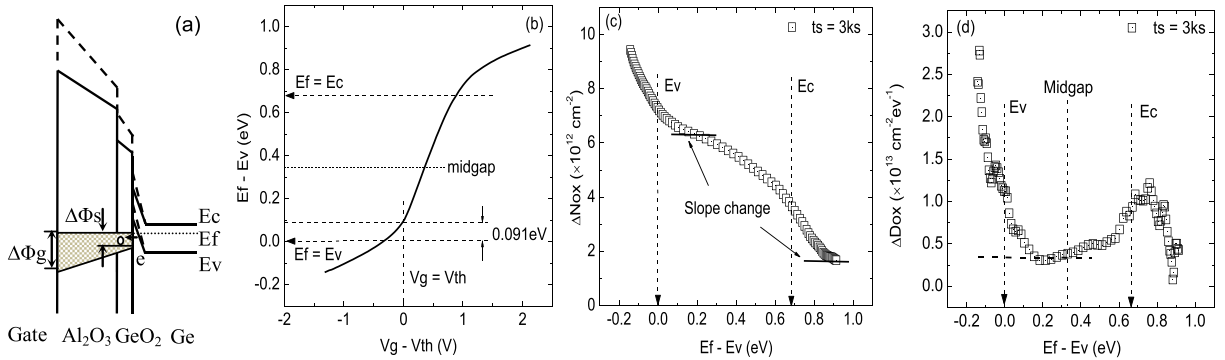


Fig. 2. (a) A schematic energy diagram before (dashed lines) and after (Solid lines) $V_{\text{discharge}}$ stepping towards positive. After the stepping, the PCs in the shaded region is below E_f and will be discharged [16], [20]. By varying $V_{\text{discharge}}$ over a large range, E_f can be swept from below E_v to above E_c at the interface. It should be pointed out that the quantization effect leads to a deviation of ground state energy levels from the E_c and E_v at the interface in Fig. 2(a). The ‘ E_c ’ and ‘ E_v ’ were used here to represent band bending, following common practice [21].

III. RESULTS AND DISCUSSION

The principle of the probing technique is illustrated in Fig. 2(a). When $V_{\text{discharge}}$ was stepped towards positive, the PCs in the shaded area fell below E_f and discharged [16], [20]. By varying $V_{\text{discharge}}$ over a large range, E_f can be swept from below E_v to above E_c at the interface. It should be pointed out that the quantization effect leads to a deviation of ground state energy levels from the E_c and E_v at the interface in Fig. 2(a). The ‘ E_c ’ and ‘ E_v ’ were used here to represent band bending, following common practice [21].

To obtain the energy distribution, $V_{\text{discharge}}$ should be converted to $E_f - E_v$ at the interface. This relationship was obtained from a 1D Schrödinger-Poisson simulator [22] and the result is given in Fig. 2(b). It should be noted that the horizontal axis of Fig. 2(b) is $V_g - V_{\text{th}}$ and $V_{\text{th}} = V_{\text{th0}} + \Delta V_{\text{th}}$ varies during discharging.

Fig. 2(c) plots the effective density of PCs, i.e. ΔN_{ox} , versus $E_f - E_v$, evaluated from $\Delta N_{\text{ox}} = C_{\text{ox}} \times \Delta V_{\text{th}}/q - \Delta N_{\text{it}}$, where ΔN_{it} is the number of generated interface states charged at $I_s = 100 \times W/L$ nA [16]. For a given stress level, ΔN_{it} does not change with $V_{\text{discharge}}$, since ΔV_{th} was always measured at the same source current for all $V_{\text{discharge}}$. The interface states were measured by the charge pumping method at 1 MHz, a rise/fall time of 20 ns, and an amplitude of 1.0 V. Their density pre- and post-stress is $6.12 \times 10^{11} \text{ cm}^{-2}$, $1.08 \times 10^{12} \text{ cm}^{-2}$ and the generated ones are $4.68 \times 10^{11} \text{ cm}^{-2}$, one order of magnitude less than the ΔN_{ox} in Fig. 2(c), so that the NBTI of Al₂O₃/GeO₂/Ge is dominated by PCs. Their effect has been taken into account in evaluating the energy distribution of PCs [16].

The energy density of PCs is evaluated from $\Delta D_{\text{ox}} = -d(\Delta N_{\text{ox}})/d(E_f - E_v)$ and a typical result is given in Fig. 2(d). As $E_f - E_v$ at the interface increases, Fig. 2(c) shows that ΔN_{ox} initially decreases rapidly, resulting in a high ΔD_{ox} in the order of $10^{13} \text{ cm}^{-2} \text{ eV}^{-1}$. As E_f approaches E_v , however, the declining rate of ΔN_{ox} reduces sharply. To assess how the PCs below E_v affect device operation, Fig. 1(c) shows that $E_f = E_v$ occurs at $V_g = -1.55$ V. As a result, the hole traps below E_v are neutral and have no effect on devices with an operational $|V_g| < 1.55$ V. For higher operation $|V_g|$ however, some PCs will be positively charged, reducing the driving $|V_g - V_{\text{th}}|$. For example, if $|V_g|$ increases from 2 to 2.5 V, Fig. 1(c) shows that 0.1 V, i.e. 20% of the $|V_g|$ -increase, will be used to compensate the PCs.

When E_f moves above E_v , Fig. 2(c) shows a slope change, leading to a low level of ΔD_{ox} between E_v and E_c . As E_f approaches E_c , however, the declining rate of ΔN_{ox} picks up again, before the second slope change above E_c . This creates a clear peak of $\sim 10^{13} \text{ cm}^{-2} \text{ eV}^{-1}$ in ΔD_{ox} near E_c . The PCs near E_c will be charged under an operation V_g and cause significant NBTI for Al₂O₃/GeO₂/Ge pMOSFETs.

To explore the relation between the PCs below E_v and those above E_v , Fig. 3 shows a comparison of their dependence on stress time. It is clear that, at short time (the symbol ‘•’), PCs are negligible above E_v , but substantial below E_v . As stress time increases, the PCs above E_v increase, but they do not shift up in parallel. To show that the PCs below E_v are insensitive to stress time, the top-dashed curve is used as an eye-guide for the top data-set with a stress time of 10 ksec. It is then shifted downward in parallel, showing good agreement with the data-set at 5 ms. It means that the

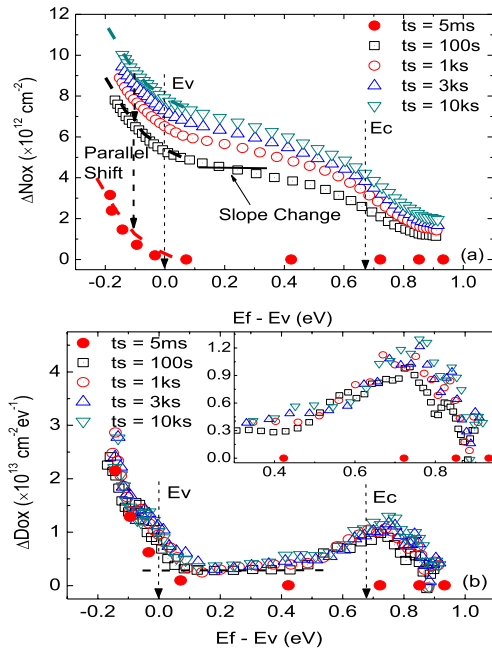


Fig. 3. A comparison of ΔNox (a) and ΔDox (b) after different stress time under $V_{\text{gst}} = -2.8\text{V}$ at 20°C . The top dashed curve is an eye-guide for the top data-set at $t_s = 10\text{ks}$. The other two dashed curves were a parallel downward shift of the top dashed curve. The symbols \bullet were obtained on a fresh device with a time for each point of 5 ms to minimize generation. The V_g was swept from positive to negative direction for this dataset.

below-Ev PCs were already fully charged after only 5 ms. The ΔDox near E_c , however, increases substantially after stress. The different stress-time dependence of defects below E_v and around E_c indicates that they could originate from different defects, although the electrical measurements reported here do not give direct information on their microscopic structure. For SiO_2/Si , it is reported that oxygen vacancy is a hole trap [23], [24] and some hydrogen-related defects can form different types of hole traps [9], [24], [25]. One may speculate that oxygen vacancy and hydrogenous defects also exist in the present $\text{Al}_2\text{O}_3/\text{GeO}_2/\text{Ge}$ sample, which awaits further investigation [26].

IV. CONCLUSION

In this letter, the energy distribution of PCs in the $\text{Al}_2\text{O}_3/\text{GeO}_2/\text{Ge}$ gate stack was characterized. The results show that ΔV_{th} can vary significantly when E_f was swept from below E_v to above E_c at the Ge interface. The energy density distribution has three features: a rapid rise when moving below E_v at the interface, relatively low between E_v and E_c , and a peak near E_c . The below- and above-Ev PCs have different dependences on stress time: the charging of below-Ev PCs is rapid and saturates, while it is slower and does not saturate for the above-Ev PCs. The density can reach $10^{13}\text{cm}^{-2}\text{eV}^{-1}$ below E_v and 20% of $|V_g|$ -increases can be screened by these PCs.

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