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Recovery and universality in NBTI from the viewpoint of traps

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Abstract

Recovery behavior of negative bias temperature instability (NBTI) was investigated. The results show that the recovery from NBTI is composed of two elements, recoverable and permanent components. The origin of the recoverable component is by the thermally activated hole detrapping from *K*-center. Interestingly, the hole trap energy distribution is Gaussian-like, resulting in universality. On the other hand, the interface states, P_{b0}- and P_{b1}-centers contribute to the permanent component. The results shed light on NBTI mechanism.

1. Introduction

Negative bias temperature instability (NBTI) has been of great interest from the perspective of MOSFET reliability. Especially, NBTI recovery behavior attracts attention and numerical papers have been published. NBTI recovery is composed of two components; recoverable and permanent components (*R* and *P*) [1]. The proposed mechanisms of *R* are the reaction-diffusion of hydrogen and the hole detrapping, and it has been controversial. On the other hand, *P* is due to the interface state [2] and fixed positive charge [3] (Strictly, *P* can recover under high temperature condition, however, in accordance with previous studies, the term "permanent" is used in this paper). *R* shows important behavior, universality [1], whose origin has not been clarified. We applied recently developed isochronal annealing and maximum entropy method (IAMEM) [4] and spin dependent recombination (SDR) to the following aims; 1. To clarify the origin of universality from the viewpoint of hole trap. 2. To confirm the origin of NBTI traps in an atomic level.

2. Theory and experiment

Theory

In this study, isochronal annealing (IA) was used. When the carrier emission probability is described by $e_p = v\exp(-E_t/kT)$, where v, E_t, k, and T are attempt-to-frequency, hole trap energy, Boltzmann constant, and absolute temperature, the basic IA equation is expressed by $\Delta V_{OT}(T_n) = \int \Delta V_{OTi}(E_t) \prod_i^n \exp\{-e_p(E_t,T_i)\Delta t\} dE_t$, where $\Delta V_{OT}(T_n)$, $\Delta V_{OTi}(E_t)$, and Δt correspond to the trapped hole contribution to ΔV_{th} of NBT stressed MOSFETs (ΔV_{OT}) after annealing at T_n, the trapped hole energy distribution just after NBT stresses, and isochronal annealing period. The above equation can not be solved due to the inverse problem. Therefore, maximum entropy method (MEM) was applied to determine the most probable $\Delta V_{OTi}(E_t)$. For details regarding MEM, see ref. [4].

Experiments

pMOSFET with oxynitride gate insulator was used (NBT stress conditions are depicted in Table I). Here, it is necessary to distinguish *R* and *P* in NBTI recovery. For this purpose, two samples (A and B in Table I) were prepared. Both *R* and *P* are locked in A, while in B, the most of *R* is eliminated and mainly *P* lefts [3]. In other words, $\Delta V_{th}(T_n)$ obtained from A containing both *R* and *P*, while *P* mainly dominates $\Delta V_{th}(T_n)$ in B. Therefore, the difference of both corresponds to *R*, $\Delta V_{OT}(T_n)$. IA starting temperature, temperature step, and Δt were 100 K, 20 K, and 600 s, respectively.

SDR spectra were recorded on C and D in Table I. It should be noted that the shorter t_s samples exhibited negligible signals probably because of little amount of traps. SDR signal is spin-dependent DCIV [3]. The microwave intensity, alternative magnetic field strength, and frequency were 200 mW, 0.5 G, and 80 Hz, respectively.

2. Results and discussion

Hole trap energy distribution and universality

Fig. 1(a) shows NBTI recovery as a function of recovery time t_r. Lines are the fitting results with the empirical equation, $\Delta V_{th}(t_r) = R + P = \Delta V_{OT}(t_r) + P = C/\{1+B(t_r/t_s)^{\beta}\} + P$ [1]. From this, only $\Delta V_{OT}(t_r)$ can be extracted. The universality in $\Delta V_{OT}(t_r)$ is plotted in Fig. 1(b). All scaled curves are well coincident, which agrees with the previous studies. IA

Table I. Samples for IAMEM and SDR.

Sample	NBT stresses (V_g=8 MV/cm)		Treatment after NBT stresses			Residual components	Experiments	
	Period t_s (s)	Temperature T_s (K)					IAMEM	SDR
A	10, 100, 1000, 10000	498	Cooled to 100 K with V_g=8 MV/cm	-	-	*R*, *P*	○	-
B	10, 100, 1000, 10000	498	Cooled to 373 K with V_g=8 MV/cm	Kept for 10^5 s at 373 K with V_g=0 MV/cm	Cooled to 100 K with V_g=0 MV/cm	*P*	○	-
C	10000	498	Cooled to 100 K with V_g=8 MV/cm	-	-	*R*, *P*	-	○
D	10000	498	Cooled to 373 K with V_g=8 MV/cm	Kept for 3000 s at 373 K with V_g=0 MV/cm	Cooled to 100 K with V_g=0 MV/cm	some of *R*, *P*	-	○

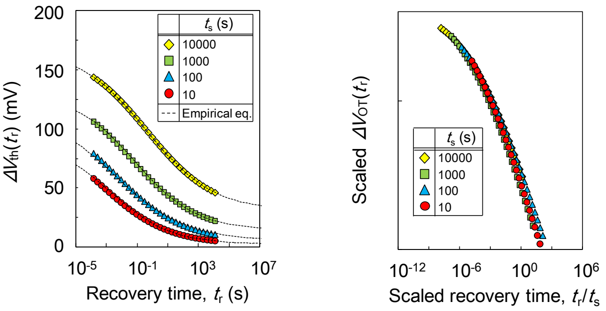

Fig. 1 (a): t_s dependent NBTI recovery. Symbols and lines are experimental data and the fitting results by the empirical equation. (b): Universality in R.

results for the samples A and B are shown in Fig. 2(a). Curves are almost flat in the sufficiently low T_n region, while they decrease with increasing T_n, and finally, become almost zero. This behavior means that all the hole traps are detected in this IA experiments. In addition, their decreases range over wide T_n region, which indicates the presence of distributed hole trap energy level.

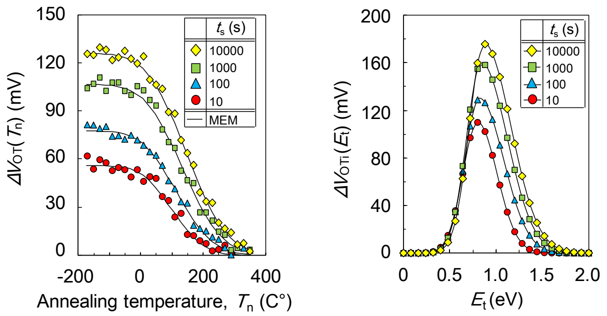

Fig. 2 (a): t_s dependent IAMEM results. Symbols and lines are experimental data and the MEM results. (b): t_s dependent hole trap energy distribution extracted by MEM.

The MEM calculation results are plotted in Fig. 2(a) (lines) and Fig. 2(b). As expected, their hole trap energy, $\Delta V_{OTi}(E_t)$ in Fig. 2(b), are broadly distributed. Note that usual IA can not provide the detailed energy distribution like Fig. 2(b), which proves the advantage of MEM. Interestingly, they are Gaussian-like. This means that when the approximation $E_t = kT\ln(\nu t_r)$ is introduced to convert E_t to t_r, $\Delta V_{OT}(t_r)$ can be easily calculated from their complementary

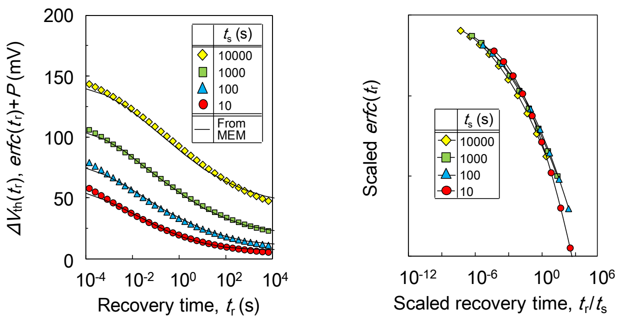

Fig. 3 (a): t_s dependent NBTI recovery. Symbols and lines are experimental data ($\Delta V_{OT}(t_r)$) and the calculations from the MEM results ($erfc(t_r)+P$). (b): Universality calculated from the MEM results.

error functions, $erfc(t_r)$. In Fig. 3(a), The experimental results (the same as Fig. 1(a)) and $erfc(t_r)+P$ (P were extracted from Fig. 1(a)) are compared. They agree fairly well. Moreover, scaled $erfc(t_r)$ plotted in Fig. 3(b) show the universality like Fig. 1(b). In other words, R behavior and universality are dominated by Gaussian-like hole trap energy distribution.

Origin of NBTI traps

SDR spectrum is shown in Fig. 4. Their complex curve shapes are well reproduced by three Gaussian curves. From the zero-crossing g-values and ΔH_{pp} (peak-to-valley distance), they can be attributed to P_{b0}-, P_{b1}-, and K-centers. The former two are well-known interface states located at the gate insulator/Si substrate interface [3]. Both centers could be produced through the interfacial Si-H bond breaking during NBT stresses. Meanwhile, K-center is the unpaired spin on Si backbonding to three nitrogen atoms. This is undoubtedly present in the bulk oxynitride film.

Interestingly, the intensity of P_b-centers exhibits small changes between C and D, while that of K-center significantly decreases, indicating that P_b-centers contributed to P, while R is dominated by K-center.

It should be noted that fixed charge proposed in the previous paper [3] could not be detected. It is possible that it has the structure like Si-O$^+$H-Si without unpaired spin (SDR inactive). This is very important point to fully understand NBTI phenomenon, therefore, more investigations are strongly required.

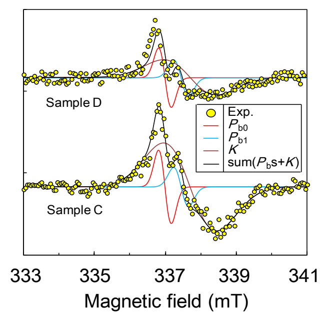

Fig. 4 SDR spectra and fitting results of sample C and D.

3. Conclusion

We have investigated R and P in NBTI recovery by IAMEM and SDR. The results show that R is determined by Gaussian-like distributed hole trap energy. In addition, the distribution can explain universality. The trap origin of R is K-center, while P_b-centers contribute to P. Unfortunately, no signal from fixed charges could be detected and further studies are required. However, the present results can shed light on NBTI mechanism.

References

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