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Real-time observation of charging dynamics in hafnium silicate films using MOS capacitance transients

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Abstract

This paper presents the results of applying a novel capacitance transient based technique to study the charge trapping dynamics of $(HfO_2)_x(SiO_2)_{1-x}$ $(0.5 \leq x \leq 1)$ high-*k* dielectric layers. We detect positive charge generation during the stress and extracted the time-varying charge dynamics. The stress induced electron traps exhibits longer time constants than the as-grown ones. The measured positive charge concentration is found to vary with hafnium concentration. Part of the positive charge is stable and can be detected by *C-V* measurements.

Keywords: capacitance transient, charge trapping, high-*k*

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1. Introduction

Hf-based gate dielectrics as high-*k* candidates are facing a series of problems such as process integration, low mobility, and threshold voltage instability. The conventional techniques [1] for characterising the charge trapping in Hf-based dielectrics, however, require a transistor structure. We have developed a novel technique [2] based on capacitance transient (*C-t*) measurement to observe charge trapping dynamics. This technique requires only a capacitor structure and therefore is convenient for fast screening.

Using this technique we identified two main characteristic types of response, as depicted in Fig. 1. Type A is associated with development of a positive charge centroid that arises as electrons are stripped from the oxide under positive gate bias. The centroid induces an image charge which is manifested by widening of the depletion region (*W*) in the substrate and hence a reduction or smearing of the measured capacitance, *C*(*t*). Type B response is associated with a negative charge centroid which is the result of rapid surface generation and subsequent tunnelling of electrons into the high-*k* film. The associated centroid induces a narrowing of W and hence more rapid recovery of C(*t*). In this paper we combine this technique with a conventional stress and sense method to study charge trapping in HfSiO films.

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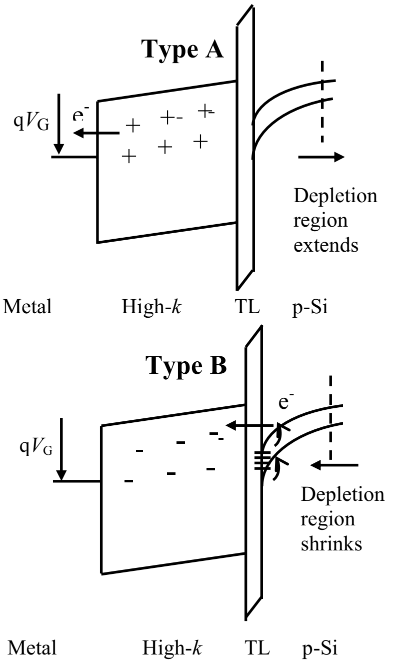

Fig. 1. Band diagram of the two types of responses identified earlier Ref. [2].

2. Experimental

HfSiO films with thickness of ~4 nm were deposited on p-type silicon by MOCVD. The substrate was treated with the IMEC clean prior to high-*k* deposition, resulting in ~1 nm chemical SiO_2 interfacial layer. After TaN gate deposition, the samples received a rapid thermal anneal in N_2 at 1030 °C for 1s. The area of the MOS capacitors used in the tests was 1×10^{-4} cm^2.

The capacitance - transient measurement system consists of a Booton 72B 1MHz and a HP4152B semiconductor analyser with IEEE 488 interface for downloading data.

3. Results and discussion

Fig. 2 (a) shows the *C-t* response of an HfSiO sample with 50% HfO_2. The sample was stressed at accumulation (-2 V) for different times prior to pulsing into deep depletion (+1 V). There are several features that can be identified. The first is the reduction in the initial capacitance C_o after stress. Secondly, the *C-t* relaxation time tends to be longer after stress. We explain these phenomena as follows. During the stress, positive charge is generated. The source for this positive charge could be related to hydrogen release [3] during the –2V stress.

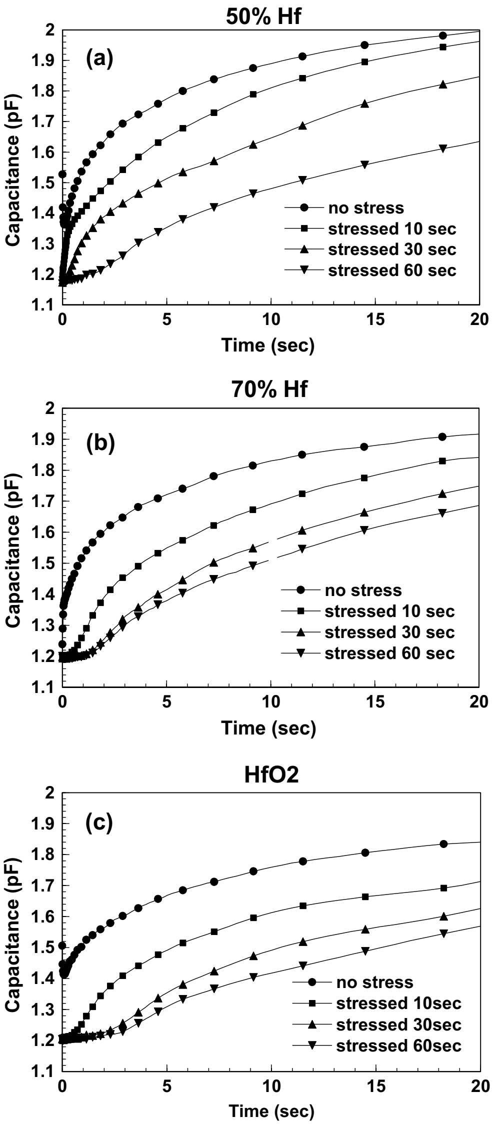

Fig. 2. Capacitance transient responses of HfSiO samples with different Hf concentration under the same stress condition.

In the meantime, electrons injected from the gate are trapped in the oxide causing negative charging which partially compensates the positive charge

(Fig. 3). When a positive going pulse is applied, the trapped electrons are driven out and positive charge is thus revealed in the oxide. The associated centroid causes the further deepening of depletion therefore the *C-t* response tends to last longer until the substrate is fully relaxed and the capacitance recovers to the equilibrium value. The lower C_o can be seen as part of the undershoot – a "type A" response as described earlier. A positive charge density of 5.3×10^{11} cm^{-2} can be estimated from the initial ΔC through the associated shift of deletion region edge (ΔW):

$$qN_t = qN_a \Delta W \tag{1}$$

where W is depletion region width, N_t is the charge density, ε_0 and ε_s are the permittivities of free space and silicon respectively, q is the electronic charge, N_a is the doping density of substrate, and C_{ox} is the oxide capacitance per unit area.

The 'flattening' of the initial *C-t* response indicates a dynamic balance between thermal generation in the Si and the influence of the charge centroid in the dielectric. The lengthening of the overall response implies that some electron de-trapping exhibits longer time constants than those associated with the well-known electron trap at approximately 1 eV from the conduction band edge [1]. Positive charge is unlikely to be generated during the deep depletion transient as the oxide field is low in this regime.

Fig. 2 (b) and (c) shows the *C-t* response obtained from HfSiO samples with higher (70% and 100%) Hf concentration under the same measurement condition. The basic trends are repeatable as observed in all samples. The figure also shows that the relaxation time is about 2 – 4 times longer for samples with higher Hf concentration, suggesting that the positive charge is related to hafnium concentration. Assuming the O content is the same, reducing Si concentration may bring more oxygen vacancies as well as strained Hf-O bonds which could acting as potential defect levels for H$^+$. The effect of different stress voltages is depicted in Fig. 4. The similarity of these two groups of curves suggests the mechanism behind the experiments is similar.

Using the technique described in [2], we are able to extract the time-varying rate of change of oxide

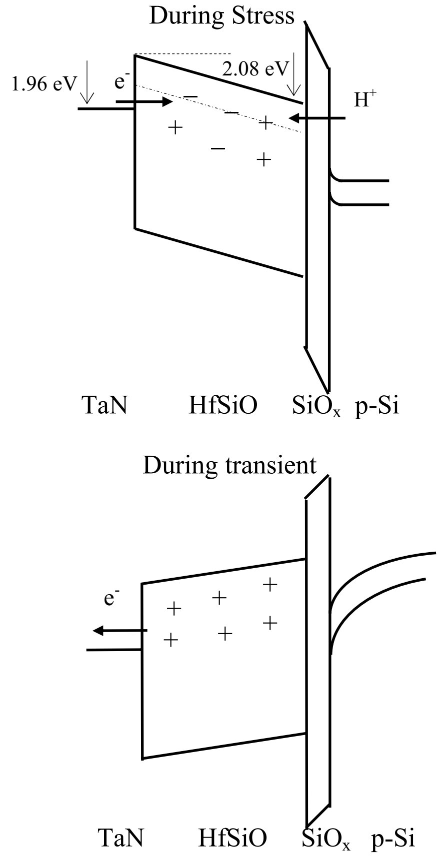

Fig. 3. Band diagrams of the sample during the stress and during the transient respectively.

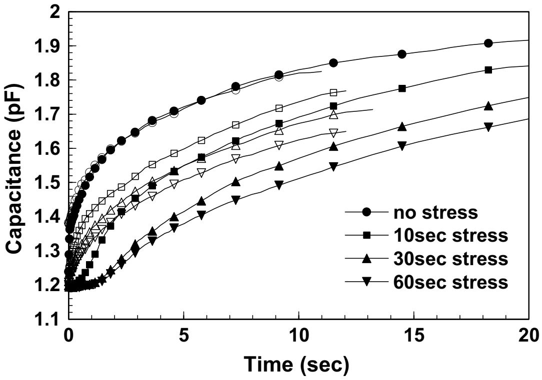

Fig. 4. *C-t* response of a HfSiO sample with 50% Hf. The solid symbols represent pulses from –2V to 1V, the open symbols represent the pulses from –1V to 1V.

charging dQ_t/dt with the following equation:

$$\frac{dQ_t}{dt} = q\varepsilon_0\varepsilon_s N_a \frac{C_{ox}}{C^3}\frac{dC}{dt} - q\varepsilon_0\varepsilon_s \frac{N_a}{T_s}\left(\frac{1}{C}-\frac{1}{C_f}\right) \qquad (2)$$

where T_s ($T_s = 2\tau_g N_a/n_i$) is the characteristic capacitance transient relaxation time, τ_g is the minority carrier generation life and n_i is the intrinsic carrier density, and C_f is the equilibrium capacitance per unit area. Fig. 5 gives an example of how the oxide charge changes during the transient for the sample with 50% Hf. For the case of the curve for the unstressed sample, the dQ_t/dt is first negative, which reflects the decrease of electron charge in the oxide. With the build up of an inversion layer, which provides electrons to tunnel into the oxide traps, the dQ_t/dt rapidly drops to negative values suggesting oxide charging starts to dominate. However for the curve of the sample after stress, the dQ_t/dt first rises up slowly and stays negative for a much longer time before it decreases to a negative value.

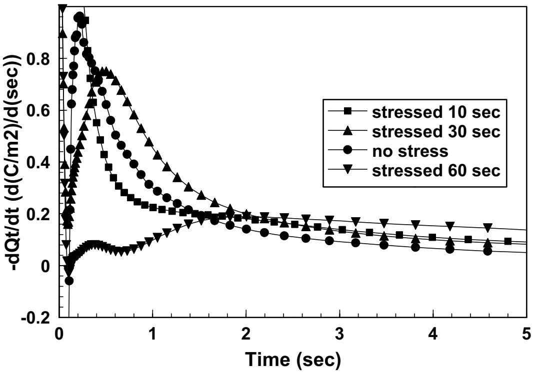

Fig. 5. The oxide charge change rate (dQ_t/dt) versus time of the HfSiO sample with 50% Hf.

C-V measurements performed before and after stress (Fig. 6) show a shift towards the negative direction indicating generation of positive charge. The charge density is estimated from the flat band voltage shift through the following equation [4]:

$$N_t = \Delta V_{FB} C_{ox} / q \qquad (3)$$

where ΔV_{FB} is flatband voltage shit. A charge density of 4.8×10^{11} cm^{-2} is estimated from a flatband voltage shift of 0.05 V.

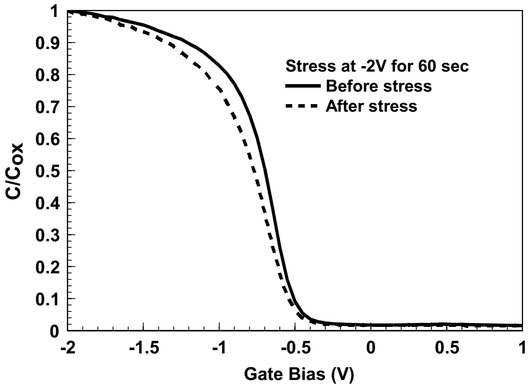

Fig. 6. C-V plots of a HfSiO sample with 50% Hf before and after 60 sec stress at –2V. The insert is C-V curves obtained from gated diodes on the same wafer.

4. Conclusions

In summary, we employed the *C-t* technique to study the HfSiO films and made the following observations: (i) positive charge generation during stress; (ii) part of the charge is stable and can be detected by *C-V* (iii) the positive charge is dependent on Hf concentration.

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References

[1] A. Kerber, E. Cartier, L. Pantisano, R. Degraeve, T. Kauerauf, Y. Kim, A. Hou, G. Groeseneken, H. E. Maes, U. Schwalke, IEEE Electron. Dev. Lett. 24 (2003) 87.
[2] S. Hall, O. Buiu, Y. Lu, IEEE Trans. Electron. Dev. 54 (2007) 272.
[3] M. Houssa, V. V. Afanas'ev, A. Stesmans, M. Heyns, Appl. Phys. Lett. 77 (2000) 1885.
[4] E. H. Nicollian, and J. R. Brews, MOS Physics and Technology, John Wiley & Sons, 1982.