Separation Method of Hole Trapping and Interface Trap Generation and Their Roles in NBTI Reaction-Diffusion Model

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INTRODUCTION

NBTI is one of the most critical reliability problems in advanced CMOS technologies. Its characterization has been corrupted by recovery effect due to the switching and measurement delays [1,2]. In order to eliminate this recovery effect, many different fast $I_d-V_g$ techniques have been developed, including the on-the-fly $I_{lin}$-trapping [3-5] and pulse $I_d-V_g$ [4,5]. However, inconsistent NBTI results and hole trapping model were obtained when performing these fast $I_d-V_g$ techniques [3-5]. In this paper, we (1) propose a separation method of hole trapping from the measured $V_t$ shift, (2) study the voltage and temperature dependency of hole trapping and interface trap generation, (3) demonstrate the three significant stages of interface trap generation in analytical H-H$_2$ NBTI Reaction-Diffusion model, and (4) clarify the influence of hole trapping on device lifetime extrapolation.

EXPERIMENTS

PMOS devices with plasma nitrided oxide SiON (EOT ~ 12Å) were fabricated using advanced CMOS process technology. The delay time of NBTI stress-measure-stress technique was reduced to as short as 1.26 ms by using Keithley 2600 series high speed Source-Measure-Units, thus providing the timing-on-the-fly NBTI characteristics minimizing recovery effect.

RESULTS AND DISCUSSION

Separation Method of $\Delta V_h$ and $\Delta V_t$

Fig. 1 shows $\Delta V_t$ as a function of stress time with various delay times ranging from 1.26 to 420 ms. It seems that $\Delta V_t$ magnitude and time exponent vary with the delay time even under the same stress conditions. This controversy can be addressed by proposing the $\Delta V_h$ is a combination of hole trapping $\Delta V_h$ and interface trap generation $\Delta V_t$, where the $\Delta V_h$ is highly modulated by the delay time. In addition, we found the difference between every two $\Delta V_t$ curves in Fig. 1 is a constant during the stress (Fig. 2), presumably due to the difference of two hole trapping levels. Based on the hole trapping-de-trapping model [6-8], $\Delta V_h$ should saturate rapidly and keep constant during the stress time. Therefore, the initial $\Delta V_h$ measured at very short stress time could be regarded as $\Delta V_h$ (Fig. 3), and the contribution of interface traps to overall $V_t$ shift without involving hole trapping could be obtained by subtracting the initial degradation magnitude from whole time evolution curve, as shown in Fig. 3. Since $\Delta V_h$ of 1.26 ms delay could be defined as $\Delta V_t$ at very short stress time, we could obtain each $\Delta V_h$ corresponding to various delays because hole trapping differences between every two delays have been given (Fig. 2). After correcting both hole trapping and recovery effect, the $\Delta V_h$ curves of various delays overlap together (Fig. 4) and exhibit the ideal time exponent of 1/6 in the classical NBTI reaction-diffusion model. Thus, we may conclude the debate on the various time exponents observed by many research groups results from the interferences from hole trapping and recovery effect in different delay time (Fig. 5).

Voltage Dependence of $\Delta V_h$ and $\Delta V_t$

Fig. 6 shows time evolution of $\Delta V_h$, having delay ~ 1.26 ms and n ~ 0.12. After subtracting hole trapping, as shown in Fig. 7, the time exponents vary from 1 to 1/6 and $\Delta V_t$ goes through three different stages as proposed in analytical NBTI Reaction-Diffusion model [7-8]. Within very short stress time, the analytical reaction-limited solution suggests n ~ 1. During intermediate stress time, the atomic hydrogen released from interface is being converted to molecular H$_2$, and gives a time exponent of 1/3. For long-term, neutral H$_2$ diffusion becomes the dominant mechanism of interface trap that limits degradation rate (n ~ 1/6). Fig. 8 plots voltage dependent $\Delta V_h$, which is in qualitative agreement with the voltage dependency of trapping model [8]. As $\Delta V_h$ increases with increase in stress voltage, it affects the device lifetime significantly at higher stress voltage (Fig. 9) compared to that at lower stress bias. It is noticed that the extrapolation without eliminating contribution of hole trapping significantly overestimates device lifetime at operation voltage.

Temperature Dependence of $\Delta V_h$ and $\Delta V_t$

Fig. 10 (a) and (b) plot the temperature dependent of ($\Delta V_{h0} + \Delta V_t$) measured by timing-on-the-fly with delay ~ 1.26 ms and $\Delta V_h$ only, respectively. Fig. 11 shows the activation energies of $\Delta V_h$ and $\Delta V_t$. $E_a$ for $\Delta V_h$ (0.109eV) are in good agreement with activation values of interface trap reported in literatures [2,6]. On the contrary, hole trapping reveals much less temperature sensitivity ($E_a$ ~ 0.04eV) than that of interface trap, also consistent with literature [9]. Fig. 10 (b) also indicates that not only the interface trap at long-term, but also at intermediate stress time are affected by temperature, as expected within R-D framework [7,8]. Thus the temperature dependence of $\Delta V_h$ suggests temperature activation for H$_2$ diffusion (governing at long-term) and H-H$_2$ conversion (dominating at intermediate stress time) are temperature activated.

CONCLUSIONS

In this study, we propose a systematic method to separate the hole trapping from measured $V_t$ shift, thus giving the ideal interface trap generation behavior without measurement disturbance. Three stages of interface trap generation have been illustrated with the analytical H-H$_2$ NBTI reaction-diffusion model, and the hole trapping has also been verified with its voltage-enhanced and temperature-insensitive properties. Finally, the lifetime extrapolation without considering the hole trapping might lead to significant lifetime overestimation.

REFERENCES

Timing-on-the-fly NBTI with stress Vg = -1.5V

<table>
<thead>
<tr>
<th>Stress Time (sec)</th>
<th>Vt Shift (mV)</th>
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</thead>
<tbody>
<tr>
<td>1.26 ms, n = 0.12</td>
<td>40</td>
</tr>
<tr>
<td>5 ms, n = 0.13</td>
<td>30</td>
</tr>
<tr>
<td>42 ms, n = 0.15</td>
<td>20</td>
</tr>
<tr>
<td>420 ms, n = 0.18</td>
<td>10</td>
</tr>
</tbody>
</table>

Recovery

Hole trapping

Ideal time exponent, n = 1/6

Delay Time (msec)

Vt Shift (mV) Stress Time (sec)

Vt = Vh + Vit

Vit only

Interface traps and hole trapping

Ea = 0.109 eV

Ea = 0.043 eV