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Energy Dependence of Interface Trap Density——Investigated by Relaxation Spectral Technique*

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Abstract: According to the definition of interface traps, a new application of relaxation spectral technique to sub-threshold swing shift and sub-threshold gate voltage shift is proposed to extract interface trap density in 1.9nm MOSFET. And thus the energy distribution of interface trap can be determined. According to the two methods, the energy profile of interface traps agrees with those reported in literature. Compared to other methods, this method is simpler and more convenient.

Key words: relaxation spectral technique; interface trap; MOS structure

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1 Introduction

Although Si-SiO_2 system has been studied for many years, the exact nature of the Si-SiO_2 interface is not yet fully understood. However, it is the fact that the degradation of the Si-SiO_2 interface under various types of stresses (such as, hot carrier, high-field stress, etc.) plays an important role in the reliability of MOSFET. Especially, with the device scaling down into deep sub-micron stages, the impact of interface on device performance becomes more important. Thus the study of interface becomes an important topic in MOS device reliability fields. To gain a deeper insight into the mechanisms of electrical characteristics degradation in MOSFET, information of the energy dependence of interface trap density is often required. Several techniques have been proposed to determine the interface trap density within the bandgap. Both AC conductance and C-V techniques[1,2] are based on measurement on large-area MOS capacitors. And they are not suitable for deep sub-micron MOSFET's. Although charge-pumping technique can give any distribution in thick gate oxide, it is complicated and difficult to be applied to ultra-thin gate oxide because charge pumping current will go through oxide and result in the failure of this method. More recently, DCIV method is also proposed to investigate energy dependence of interface trap density. However, it is complicated[3] because too much fit parameters are used. So it is interesting to find a simpler technique for the extracting of trap parameters and its energy distribution.

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In the former works[4~6], relaxation spectral (RS) technique was proposed by Xu and Tan to extract trap parameters. However, energy distribution of trap was not considered. In this paper, we extend RS technique further and apply it in both sub-threshold swing shift and the sub-threshold voltage shift to extract energy distribution of interface traps. It is proved to be effective and simple. It also can provide on-line measurement of interface trap and its energy profile.

2 Theory

In sub-threshold region, the drain current is dominated by diffusion. It can be described as[2]:

$$I_D = \mu_n\left(\frac{W}{L}\right)\frac{aC_{ox}}{2\beta^2}\left(\frac{n_i}{N_A}\right)^2(1-e^{-\beta V_D})e^{\beta\psi_S}(\beta\psi_S-1)^{1/2} \quad (1)$$

where ψ_S is the band bending at the surface. μ_n, W, L, a, β, N_A, n_i, and C_{ox} are the constants.

From Eq. (1), it can be seen that near exponential dependence of I_D upon gate bias. Usually, defined the sub-threshold swing, S.

$$S = \ln 10\frac{dV_G}{d\ln I_D} = S_0 \times \frac{1+(C_d+C_{it})/C_{ox}}{1+C_d/C_{ox}} \quad (2)$$

where S_0 is the sub-threshold swing with no interface traps. C_d is the depletion layer capacitance, C_{it} is the interface traps capacitance, $C_{it} = qD_{it}$, D_{it} is the interface trap density at a given trap energy level, $D_{it} = \frac{1}{q}\times\left.\frac{dQ_{it}}{dE}\right|_{\psi_S}$.

Combination of Eqs. (1) and (2), it can be seen that interface trap will have an obvious influence on transfer characteristics. The effects of interface trap can be judged from both the sub-threshold swing shift and the sub-threshold voltage shift. So, with the help of RS technique, two different methods can be used to extract the energy dependence of interface traps with the consideration of the effects of interface traps.

2.1 Extracting N_{its} from sub-threshold gate voltage shift

Interface traps in the upper half of the band gap are generally believed to be acceptors, and those in the lower half of the band gap are donors. This assumption has been accepted by researchers[7,8]. McWhorter et al proposed a method[9]. For example, for nMOSFETs, when a voltage is applied in gate, the band is bent. When the band bending at the surface $\psi_S = \phi_B$, we think that interface trap has no influence on sub-threshold voltage shift. With voltage increasing, when $\phi_B < \psi_S < 2\phi_B$, interface trap level lying in Fermi level (E_F) and midgap (E_i) will be filled by charges which vary in number, resulting in the effect of stretching out the sub-threshold-current curve. A stretch-out voltage V_{so} can be defined as the voltage difference between the midgap and threshold points:

$$V_{so} = V_{th}(\psi_S) - V_{mg}(\phi_B) \quad (3)$$

Interface trap density increases with stress time. Thus, the stretch-out voltage V_{so} will be different under different stress time. This means, sub-threshold voltage shift due to interface trap, will result in the difference of stretch-out voltage on respective subthreshold-current curves:

$$\Delta V_{Nit} = (V_{so})_2 - (V_{so})_1 \quad (4)$$

The increasing of interface traps can be determined by $\Delta N_{it} = \Delta V_{Nit}C_{ox}/q$, where ΔN_{it} represents the increase in the total number of interface traps charge between the midgap and the threshold. C_{ox} is the oxide capacitance.

According to first-order rate equation and relaxation spectroscopy theorem[6], the spectroscopy density function can be written as:

$$\Delta_p V_{Nit}(F) = \Delta V_{Nit}(k_pF) - \Delta V_{Nit}(F) = \frac{q}{C_{ox}}N_{its}(e^{-\sigma_{it}\rangle F} - e^{-\sigma_{it}\rangle k_pF}) \quad (5)$$

where $F = \int_0^t \frac{J}{q}dt$ is the electron fluence, J is the stress current density through gate oxide layer, and t represents stress time. k_p is a constant. N_{its} is sat-

urate interface trap density. $\langle\sigma_{it}\rangle$ is the average generate/capture cross-section. For the peak position, $F = F_m$, according to the extreme value condition, $\frac{\partial \Delta_p V_{Nit}(F)}{\partial F} = 0$, the trap parameters can be obtained as

$$\langle\sigma_{it}\rangle = \frac{\ln(k_p)}{k_p - 1} F_m^{-1} \quad (6)$$

$$N_{its} = \frac{C_{ox}}{q} \Delta_p V_{Nit}(F_m) [k_p^{k_p/(1-k_p)}(k_p - 1)]^{-1} \quad (7)$$

Based on above analysis, the distribution of total interface trap can be obtained by varying threshold point. This means, for different band bent ψ_S, the corresponding interface trap density can be determined, and thus its energy distribution at bandgap range can be obtained.

2.2 Extracting D_{its} at a given trap level from sub-threshold swing shift

Because the interface trap affects both gate voltage and sub-threshold swing, interface trap can be also extracted from sub-threshold swing shift.

The shift of sub-threshold swing caused by interface trap charges can be written[5] as:

$$\Delta S(F) = S(F) - S(0) = \frac{qS_0}{C_{ox} + C_d} D_{it}(F) \quad (8)$$

$$D_{it}(F) = D_{its}[1 - \exp(-\langle\sigma_{it}\rangle F)] \quad (9)$$

where F is the electron fluence, $D_{it}(F)$ is the interface trap density, D_{its} is the saturate interface trap density.

According to the difference sampling spectroscopy theorem[6], Eq. (8) can be rewritten as

$$\Delta_p S = \Delta S(k_p F) - \Delta S(F) = \frac{qS_o D_{its}}{C_{ox} + C_d}[e^{-\langle\sigma_{it}\rangle F} - e^{-\langle\sigma_{it}\rangle k_p F}] \quad (10)$$

Similar to the analysis in section 2.1, for peak position F_{ip}, we have

$$D_{its} = \frac{C_{ox} + C_d}{qS_o} \Delta_p S(F_{ip}) [k_p^{k_p/(1-k_p)}(k_p - 1)]^{-1} \quad (11)$$

$$\langle\sigma_{it}\rangle = \frac{\ln k_p}{k_p - 1} F_{ip}^{-1} \quad (12)$$

From above discussion, it can be seen that D_{its} is obtained for a given trap energy level. In other words, for different surface potential varying with gate voltage, trap energy level $E_{it} = q\psi_S - q\phi_B$, then the corresponding D_{its} for different trap energy level, E_{it}, can be extracted with above method. So, applying RS technique to sub-threshold swing, the energy distribution of interface trap density can be easily determined.

2.3 Relation between N_{its} and D_{its}

From above analysis, sub-threshold swing shift can be used to extract D_{its} for a given surface potential, and the gate voltage shift can be used to extract total N_{its} lying between midgap($\psi_S = \phi_B$) and at a given surface potential($\phi_B < \psi_S < 2\phi_B$). Also, according to the definition of D_{its}, for a given surface potential, ψ_S, we have the following relation:

$$N_{its}|_{\psi_S} = \int_{\phi_B}^{\psi_S} D_{its} dE_{it} \quad (13)$$

or

$$D_{its}|_{\psi_S} = \left.\frac{\partial N_{its}(E)}{\partial E}\right|_{\psi_S} \quad (14)$$

3 Experiment results

3.1 Sample

Experiments were performed by using HP4156B semiconductor parameter analyzer. The samples were n-channel MOSFETs with a channel width of 10μm and a channel length of 10μm. The substrate was p-type silicon with a resistivity of approximately 0.1Ω·cm. The gate oxide thickness was approximately 1.9nm. Flat-band voltage is approximately equal to −0.95V. Stress was interrupted after preseting time intervals and transfer characteristics were measured. The gate voltage sweep range was just enough to reveal the sub-threshold characteristics, but not large enough to disturb the charge state of the gate oxide.

3.2 Experiments

In order to obtain energy profile of interface

trap, different surface potential are firstly chosen. For example, surface potential varies from 1.3ϕ_B to 2ϕ_B, where $\phi_B = \frac{2k_BT}{q}\ln(\frac{N_A}{n_i})$, N_A is the channel doping, n_i is the intrinsic carrier concentration. Then, calculating the corresponding sub-threshold current as a function of surface potential with Eq. (1), mapping these current values on the measured transfer characteristics ($V_G - I_D$) curves, gate voltages, and the corresponding sub-threshold swings which resulted in these current value can be obtained with Eq. (2). In this way, sub-threshold swing shift and sub-threshold gate voltage shift can be obtained for different stress time.

From Eq. (4) in section 2.1, sub-threshold gate voltage shift induced by interface trap is obtained, as shown in Fig. 1(a) for different surface potential, where ψ_S varies from 1.3ϕ_B to 2ϕ_B considering the limit of measurement instrument. The corresponding proportional differential curve and its result are obtained with Eqs. (5) and (7), as shown in Fig. 1(b) and (c).

From Eq. (8) in section 2.2, sub-threshold swing shift is given in Fig. 2(a) for different surface potential. The corresponding proportional differential curve and its result are obtained with Eqs. (10) and (11), as shown in Figs. 2(b) and (c). Also, the distribution of $N_{its}(E)$ obtained from integral $D_{its}(E)$ is given in Fig. 2(c).

Because of the limitation of measurement instruments, $N_{its}(E)$ is obtained by integral $D_{its}(D)$ from 1.3ϕ_B to 2ϕ_B, not from ϕ_B to 2ϕ_B. So, it is reasonable that $N_{its}(E)$ in Fig. 1(c) is larger than $N_{its}(E)$ in Fig. 2(c). Also, the above two methods have good agreement.

To further verify our results, we compare our results with those in Refs. [3, 10~ 12]. Although the extraction of interface trap density distribution is experimentally unreliable near the band edges, it is quite clear that same trend exists in these methods: there exists a large interface trap density $D_{its}(E)$ near midgap. The detail difference may come from the difference of processing, oxide thickness and extracting methods.

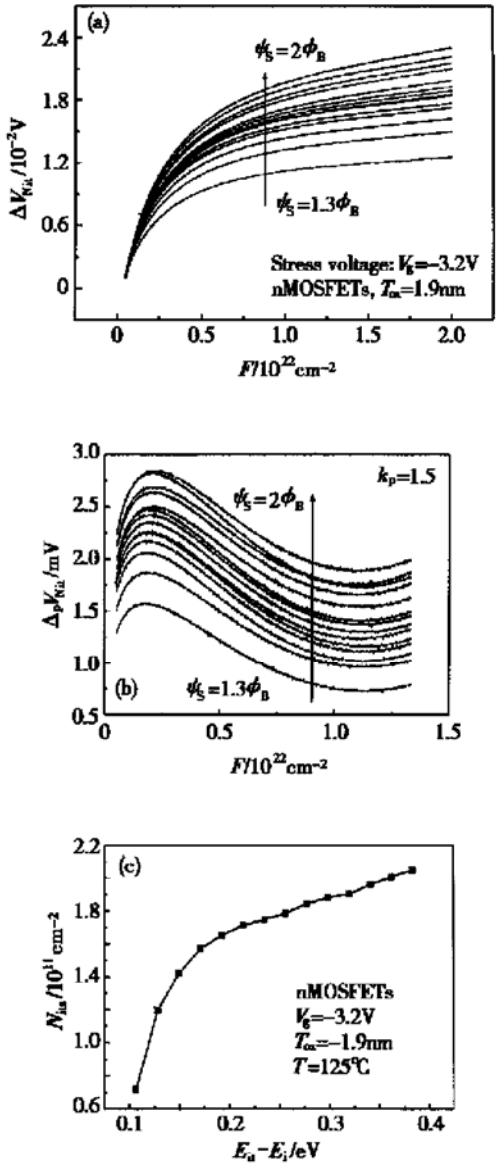

Fig. 1 (a) Sub-threshold gate voltage shift curve induced by interface trap; (b) Proportional differential curve for sub-threshold gate voltage shift induced by interface trap; (c) Energy distribution of the density of saturation charged interface trap, N_{its}.

3.3 Results

Based on above discussion, both sub-threshold swing shift and sub-threshold gate voltage shift can be used to extract the energy profile of interface trap with the help of RS technique. It is found that the extraction process of sub-threshold swing shift and sub-threshold gate voltage shift can be

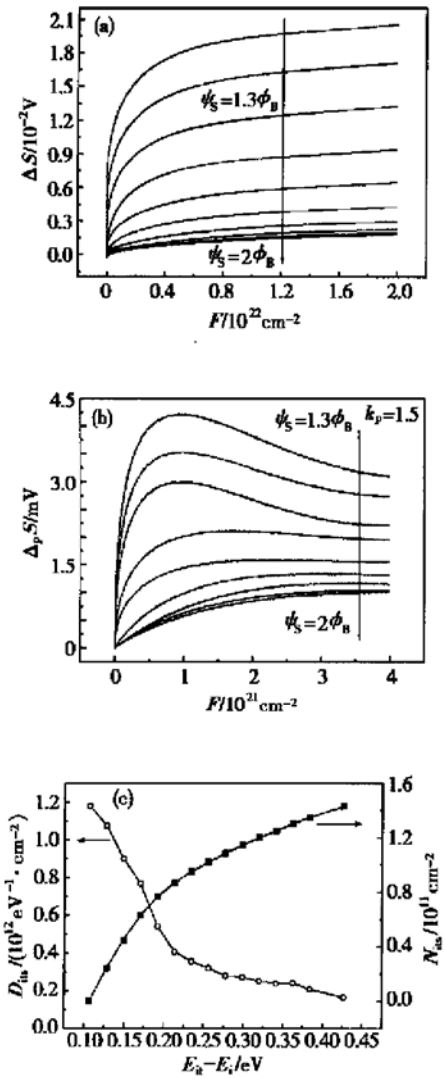

Fig. 2 (a) Sub-threshold swing shift curve for different surface potential; (b) Proportional differential curve for sub-threshold swing shift; (c) Energy distribution of interface trap density $D_{its}(E)$ and also energy distribution of the density of saturation charged interface trap, N_{its}, obtained by integration of $D_{its}(E)$

programmed easily. And energy profile of interface trap can be also extracted by programming RS technique. So, our method can provide on-line measurement of interface trap density and its energy profile. Comparison with other methods, such as, DCIV method, our method is simpler and easier to be used because only transfer characteristic is involved while too much fitting parameters are needed in DCIV method[3].

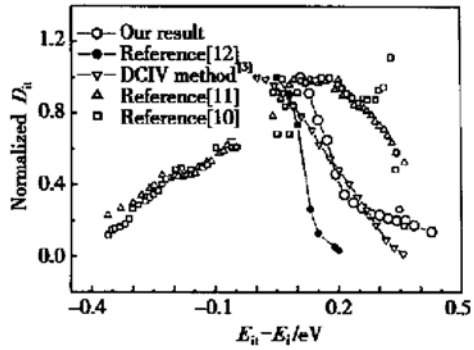

Fig. 3 Normalized energy distribution of interface trap

4 Conclusions

In the paper, a new method to extract the energy profile of interface traps is proposed with application of Relaxation Spectral technique. Compared to other methods, our method is proved to be reasonable, simpler, and more convenient.

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利用弛豫谱技术对界面陷阱密度和其能量分布的研究*

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摘要: 基于界面陷阱的定义, 通过分别对亚阈值摆幅漂移和亚阈区栅电压漂移采用弛豫谱技术有效地提取了1.9nm MOS 结构中的界面陷阱密度和它的能量分布. 发现这两种方法提取的界面陷阱密度的能量分布是自洽的, 同时也与文献报道的 DCIV 等方法的结果是一致的. 与其它的提取方法相比, 采用弛豫谱技术的这两种方法更加简单和方便.

关键词: 弛豫谱技术; 界面陷阱; MOS 结构

PACC: 7340Q; 7100

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