Modeling of Enhanced 1/f Noise in TFT with Trap Charges

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Abstract—We have investigated the influence of existing trap states of TFT on device characteristics with use of the compact model HiSIM-TFT. Special focus is given on the 1/f noise characteristics, where it is found the Vgs dependence of the 1/f noise characteristics is very sensitive to the trap density distributions. We have successfully extracted high density of the shallow trap states with the measured 1/f noise characteristics.

Keywords-component; TFT; compact model; trap density; 1/f noise characteristics; I-V characteristics

I. INTRODUCTION

It has been demonstrated that the recrystallization of the ploy silicon results in high TFT performance valid even for RF applications [1]. This enables integration of complete circuits on a single display. This expands capability of the integrated displays for advanced applications. However, it is known that remained trapped states at grain boundaries of the poly silicon cannot be removed completely and influence on device performances. Here our purpose is to model the influence of the inevitable remained trap states on the device performances. For this purpose we have measured the 1/f noise characteristics, which are sensitive to the interface condition of MOSFET [2]. The different measured characteristics of the 1/f noise of TFTs in comparison to bulk MOSFETs without the trap sites are investigated with the compact model HiSIM-TFT, considering the trap density within the Poisson equation explicitly [3]. It is shown that the trap distribution can be well reproduced by adjusting the trap-density distribution within the bandgap.

II. COMPACT MODEL HiSIM-TFT WITH TRAP DENSITY

We have developed the TFT model HiSIM-TFT based on the surface-potential description [3]. The trap density is incorporated into the Poisson equation, which is solved iteratively

\[
\frac{d^2 \phi}{dx^2} = -\frac{q}{\varepsilon} \left( p - n + N_D^+ - N_A^+ + N_{TA}^+ - N_{TD}^+ \right)
\]

where the trap densities (N_D^+ and N_A^+) are modeled with a simple distribution function which decreases linearly in the bandgap as depicted in Fig. 1.

\[
g_A(E) = g_c \exp \left( \frac{E_F^e - E_C}{E_S} \right)
\]

\[
g_D(E) = g_c \exp \left( \frac{E_C - E_F^h}{E_S} \right)
\]

where \(E_F^e\) and \(E_F^h\) are the quasi-Fermi energy for electrons and holes, respectively. \(E_C\) and \(E_V\) are the energy of the bottom of the conduction band and that of the top of the valence band, respectively. \(E_S\) and \(g_c\) are the inverse slope of the trap states and the trap states density at \(E_C\) and \(E_V\), respectively. By integrating the product of the Fermi-Dirac distribution function and each of (2) and (3) across the band gap, equations to describe the density of ionized acceptor-type traps and donor-type traps are obtained as [4]

\[
N_{TA}^- = N_A^- \cdot \exp \left( -\frac{E_F^e - E_{TA}^-}{E_S} \right)
\]

\[
N_{TD}^+ = N_A^+ \cdot \exp \left( -\frac{E_F^h - E_{TM}^+}{E_S} \right)
\]

\[
N_A^+ = g_c \cdot E_S \cdot \frac{k \cdot T}{\sin \left( \frac{q \cdot E_S}{k \cdot T} \right)}
\]

where \(T\) and \(k\) are the lattice temperature in kelvin and the Boltzmann constant, respectively. For compact modeling, the relation is rewritten with the quasi-Fermi potential, which is considered to be a function of electrostatic potential [5].

The potential distribution along the depth direction is obtained by solving the Poisson equation at the source side and the drain side of the channel under the quasi-gradual-channel approximation. By integrating depletion charges and trap charges in the poly-Si layer from the surface to the bottom of
the backside, the relation between the surface potential and the backside potential are derived as

\[
\phi_b = \phi_S - \frac{q}{2e_{\text{Si}}} \frac{1}{r_{\text{Si}}} \left( N_A + \frac{n_i}{N_A} + N_{\text{TAT}} - N_{\text{TDD}} \right) \tag{7}
\]

where \( n_i \) is the intrinsic carrier density, \( \phi_S \) is the surface potential, and \( t_{\text{Si}} \) is the silicon-layer thickness. Once the potential values are known at the source side and the drain side, all device characteristics (currents, charges, capacitances) are calculated as a function of these potential values [6].

Influence of these trapped charges on device characteristics is well confirmed by the increased subthreshold swing as well as the reduction of the current under the strong inversion condition. Calculated \( I_{\text{ds}}-V_{\text{gs}} \) characteristics are shown in Fig. 2 for three different trap distributions (see Fig. 1) together with without the trap.

![Fig.1. Two different trap types (the donor-like and the acceptor-like) with three different density-state distributions (a, b, c) within the bandgap approximated by a linear function.](image1)

![Fig.2. Calculated \( I_{\text{ds}}-V_{\text{gs}} \) characteristics with three trap densities depicted in Fig. 1. The dashed line shows the result without traps.](image2)

II. 1/F NOISE ANALYSIS

Measured 1/f noise normalized by the drain current \( I_{\text{ds}} \) and the device size are shown as a function of \( V_{\text{gs}} \) in Fig. 3 together with the \( I_{\text{ds}}-V_{\text{gs}} \) characteristics. It is recognized that the high trap density induces the strong degradation of the measured \( I_{\text{ds}}-V_{\text{gs}} \) characteristics and the increase of the 1/f noise at the same time as shown by thick solid lines.

Fig. 4 compares measured normalized 1/f noise intensity of a TFT to a bulk MOSFET as a function of \( V_{\text{gs}}-V_{\text{th}} \) where \( V_{\text{gs}} \) is the threshold voltage. The normalized noise intensity represents approximately the strength of the trap density [7]. Not only increase of the noise intensity but also accompanied reduction of the \( V_{\text{gs}} \) dependence is observed, namely the 1/f noise does not reduce with increased \( V_{\text{gs}} \) as expected from the silicon MOSFET.

![Fig.3. Measured (a) \( I_{\text{ds}}-V_{\text{gs}} \) and (b) normalized 1/f noise characteristics as a function of \( V_{\text{gs}} \) for five different TFTs of the same size on a wafer.](image3)

![Fig.4. Measured normalized 1/f noise intensity as a function of \( V_{\text{gs}}-V_{\text{th}} \) for a TFT and a bulk MOSFET, where \( V_{\text{th}} \) is the threshold voltage.](image4)
Modeling of the 1/f noise is done by considering the carrier distribution along the channel [5]. The final equation is written as a function the drain current $I_{ds}$

$$S_{1/f}(f) = \frac{1}{(L-\Delta L)W} \sum_{k} \left\{ \frac{1}{N_s + N_l} \left( N_s + N_l \right) \left( N_s + N_l \right)^{-1} \right\}$$

where $N_s$, $N_l$, and $N^*$ are the carrier concentration at the source side, at the drain side, and the averaged value, respectively.

With the simplified linearly decreasing function for the trap-state density depicted in Fig. 1, HiSIM-TFT reproduces measured $I_{ds}$-$V_{gs}$ characteristics as shown in Fig. 5 for the case shown by the thick line in Fig. 3a. Results for two different $V_{gs}$ values are depicted as examples. Fig. 6 compares calculated 1/f noise characteristics with the same trap density used for the $I_{ds}$-$V_{gs}$ calculation to measurements shown by the thick line in Fig. 3b. Obvious discrepancy is detected for large $V_{gs}$ values as shown by an arrow. For comparison the calculated result without the trap density is depicted together. The discrepancy cannot be removed by adjusting the trap density by changing $g_c$ and $E_i$ in Eqs. (2) and (3).

Fig. 7a shows the correlation between the density of states for the acceptor-like trap states and the band structure. For small $V_{gs}$ values, the Fermi level, where the most occupation of trapping occurs, lies nearly in the middle of the bandgap. Therefore the deep trap states are mostly responsible for the device characteristics. For large $V_{gs}$ values, on the contrary, the Fermi level approaches to the conduction-band edge, resulting in increased occupations of the shallow trap states as can be seen in Fig. 7b.

Fig. 8 shows additional shallow trap states considered, where the deep trap states are kept the same. Three different trap-state distributions are studied. Calculated trap densities for the corresponding trap distributions are shown in Fig. 9 as a function of $V_{gs}$. Calculated $I_{ds}$-$V_{gs}$ characteristics with the new trap density including the additional shallow trap states are depicted in Fig. 10. Influence of the shallow trap states is not so drastic for the current. Calculated 1/f noise characteristics are compared with measurements in Fig. 11. It is seen that the shallow trap states are much more sensitive to the noise characteristics of large $V_{gs}$. It can be concluded that the measured noise characteristics of TFT can be well reproduced by adjusting the additional high shallow trap tail densities. Thus more detailed investigation of the trap states is possible with the noise characteristics.

![Graph 5: Comparison of calculated $I_{ds}$-$V_{gs}$ characteristics with HiSIM-TFT (lines) to those of measurements (symbols).](image)

![Graph 6: Calculated normalized 1/f noise intensities as a function of $V_{gs}$. The thick solid line shows the calculated result with trap density extracted from the measured $I_{ds}$-$V_{gs}$ results. Circles are measured data.](image)

![Graph 7: Linearly distributed density of acceptor-like trap states within the bandgap and the Fermi level depicted (a) for relatively small $V_{gs}$ and (b) for relatively large $V_{gs}$. For relatively small Vgs the Fermi level lies nearly in the middle of the bandgap. The large $V_{gs}$ causes strong band bending, resulting in the Fermi-level movement to the conduction-band edge. This results in the increase of the shallow trap occupation.](image)
**III. CONCLUSION**

We have studied the $1/f$ noise characteristics of TFTs experimentally and theoretically. By considering the trap density in the Poisson equation, both measured $I_{ds}-V_{gs}$ characteristics and $1/f$ noise characteristics can be well reproduced. To reproduce the measured $1/f$ noise characteristics under large $V_{gs}$ condition, the shallow trap states must be considered. For the $I_{ds}-V_{gs}$ characteristics, the mobility plays an important role, which conceals the influence of the trap density. Thus it can be concluded that the noise investigation is a powerful method to extract the trap density of states of devices with high density of trap states.

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