Determination of Polysilicon Gate Doping in High-κ or Oxynitride MOSFETs with Gate Electrode Fermi-Level Pinning

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1. Introduction

High-κ (e.g. HfO₂) and oxynitride films are expected to replace SiO₂ as the gate dielectric for power-constrained CMOS technologies beyond the 90-nm node [1], and CMOS devices with poly-Si gate electrodes are being considered for possible near-term solutions [2]. The development of these technologies requires accurate extraction of parameters such as EOT and the active poly-Si doping density Npoly. Fitting a theoretical model to experimental C-V data is usually used to extract these parameters, and the accuracy with which extractions can be done relies in part on the assumptions made in the model. In this work, a one-dimensional model of the poly-Si/dielectric/Si structure is used to demonstrate the effect of electrically active interfacial charges at the poly-Si/dielectric interface (Qgo) on the extracted EOT and Npoly. We show that fitting experimental C-V data to a model that does not account for Qgo may result in excellent agreement between the model and measured C-V curves, but non-physical values of EOT and Npoly. For the technologically important cases of high-κ or heavily nitrided SiON gate dielectrics, where a substantial Qgo density the poly-Si/dielectric interface has been invoked to explain large Vth shifts and is often discussed in the framework of gate electrode Fermi-level pinning [3], the use of a C-V model which accounts for this charge is required. We present a systematic examination of the errors in extracted EOT and Npoly when these charges are not accounted for in the C-V model.

2. The Model

Fig. 1 illustrates the poly-Si/dielectric/Si structure including the referenced potential drops across the regions of interest. Global equilibrium, Gauss’s law and Poisson’s equation in the Si and poly-Si regions are used to calculate Qgo, Qq, φi and φs as a function of gate voltage Vg by solving the following set of equations using a Newton’s method:

\[ Q_{go} + Q_q + Q_{pol} - Q_f = 0, \quad V_g = V_{fb} + \phi_i - \phi_s + V_{ac} \]  
(1)

\[ \varepsilon_{ac} \frac{V_{ac}}{EOT} = \frac{Q_{go} + Q_f}{\varepsilon_{ox}} - \frac{V_{ac}}{EOT} = Q_{go} + Q_f \]  
(2)

\[ Q_f = F(\phi_f, N_{pol}), \quad Q_g = F(\phi_s, N_{sub}), \quad C_g = \frac{\partial Q_f}{\partial V_g} \]  
(3)

Analytical expression of \( F(\phi N) \) is found from the solution of Poisson’s equation assuming uniform doping density in the Si channel and poly-Si gate. It is assumed that donor-like traps are located near \( E_c \) and acceptor-like traps are located near \( E_F \) (see Fig. 1), following the results in [3]. This enables the simplifying assumption that the \( Q_{go} \) is approximately bias independent from \( V_{fb} \) to strong inversion.

3. Results and Discussion

C-V curves for \( p^+ \)-poly-Si/insulator/n-Si (pMOS) and \( n^+ \)-poly-Si/insulator/p-Si (nMOS) structures are calculated for \( EOT = 10 \AA, N_{sub} = 5 \times 10^{12} \text{ cm}^{-2} \), and \( N_{poly} = 10^{20} \text{ cm}^{-2} \). The interfacial charge \( Q_{go}/q \) was varied in the range 0 to \( 2 \times 10^{13} \text{ cm}^{-2} \) and set to be positive for pMOS structures and negative for nMOS structures. These polarities were shown experimentally to have the biggest impact on poly-Si depletion and threshold voltage for pMOS and nMOS devices, and are related to the chemistry of interface formation between the poly-Si gate and a given dielectric [3]. Representative simulated C-V curves are shown in Fig. 2. In order to demonstrate the error committed in the determination of EOT and Npoly when the C-V data is fitted to a model that does not account for \( Q_{go} \), a widely accepted C-V fitting routine (NCSU CVC[4]) was used to extract the EOT, Npoly and Vfb from simulated C-V curves generated above for each value of \( Q_{go} \). C-V numerical data and NCSU CVC best fits are shown in Fig. 3 for pMOS devices with \( Q_{go}/q = 0 \) and \( +10^{13} \text{ cm}^{-2} \). The CVC extracted EOT, Vfb and Npoly from C-V curves produced by the model used here are plotted versus \( Q_{go} \) in Fig. 4. It is shown that \( N_{poly} \) is underestimated and EOT is significantly overestimated compared to original simulation parameters when \( Q_{go} \) is non-zero. The error between nominal and extracted values increases with increasing \( Q_{go} \). A similar behavior of NCSU CVC extracted \( N_{poly} \) as a function of nitrogen dose in SiON dielectrics was obtained in [5] for pMOS devices. In light of the results shown here and the model proposed by Wang et al.[6], that \( Q_{go} \) is proportional to nitrogen concentration at the poly-Si/SiON interface, the “apparent” reduction of active poly-Si gate doping with increasing nitrogen observed in [5] might be non-physical. In Fig. 5, the flatband voltage \( V_{fb} \) is plotted versus \( Q_{go}/q \) for different EOT assuming \( Q_{go}/q = 10^{11} \text{ cm}^{-2} \). Such plot may be used to estimate the \( Q_{go}/q \) density for a given experimental \( V_{fb} \) shift. Example fit to SiO₂ and Al₂O₃ data (from Ref. 7) is shown in Fig. 6.

4. Conclusions

The active interfacial charges at the poly-Si/dielectric interface have been shown to have significant impact on the determination of EOT and active poly-Si gate doping density. Although an excellent fit may be obtained between C-V data and models that do not account for these charges, non-physical values of \( N_{poly} \) and EOT result.
Fig. 1 Schematic of poly-Si/dielectric/Si structure. \( Q_{fo} \) is the effective fixed oxide charge and \( Q_{go} \) is the interfacial charge density at the poly-Si/dielectric interface.

Fig. 2 Representative simulated C-V curves for pMOS (a) and nMOS (b). The poly-Si doping density \( N_{poly} = 10^{20} \text{ cm}^{-3} \). The presence of \( Q_{go} \) at the poly-Si/dielectric interface results in \( V_{fb} \) shift and additional poly-Si depletion in strong inversion of \( p^{+}-\text{poly-Si}/n\text{-Si} \) and \( n^{+}-\text{poly-Si}/p\text{-Si} \) structures.

Fig. 3 C-V curves simulated using a model that account for \( Q_{go}/q \) ((1)-(3)) and best fits using NCSU CVC tool. (a) \( Q_{go}/q=0 \), (b) and (c) fitting bias range from accumulation to inversion and \( V_{fb} \) to inversion, respectively, for \( Q_{go}/q=10^{13} \text{ cm}^{-2} \).

Fig. 4. NCSU CVC extracted parameters from simulated C-V’s with different \( Q_{go}/q \): (a) EOT, (b) \( N_{poly} \), (c) error at best fit.

Fig. 5 Simulated \( V_{fb} \) vs \( Q_{go}/q \) for different nominal \( N_{poly} \).

Fig. 6 Data and CVC best fits for SiO\(_2\) and Al\(_2\)O\(_3\) dielectrics C-V data [7].

References