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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. HfO_2) and oxynitride films are expected to replace SiO_2 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 N_{poly}. 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 (Q_{go}) on the extracted *EOT* and N_{poly}. We show that fitting experimental *C-V* data to a model that does not account for Q_{go} may result in excellent agreement between the model and measured *C-V* curves, but non-physical values of *EOT* and N_{poly}. For the technologically important cases of high-κ or heavily nitrided SiON gate dielectrics, where a substantial Q_{go} density the poly-Si/dielectric interface has been invoked to explain large V_t 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 N_{poly} 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 Q_s, Q_p, ϕ_s and ϕ_p as a function of gate voltage V_g by solving the following set of equations using a Newton's method:

$$Q_{fo} + Q_s + Q_{go} + Q_p = 0\,,\quad V_g = V_{fb} + \phi_s - \phi_p + V_{ox} \qquad (1)$$

$$\varepsilon_{ox}\frac{V_{ox}}{EOT} = Q_{go} + Q_p\,,\quad -\varepsilon_{ox}\frac{V_{ox}}{EOT} = Q_{fo} + Q_s \qquad (2)$$

$$Q_p = F(\phi_p, N_{poly}), Q_s = F(\phi_s, N_{sub}), C_g = \partial Q_p / \partial V_g \qquad (3)$$

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_V (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 (*p*MOS) and n^+-poly-Si/insulator/*p*-Si (*n*MOS) structures are calculated for *EOT* =10Å, $N_{sub} = 5\times10^{17}$ cm^{-3}, and $N_{poly} = 10^{20}$ cm^{-3}. The interfacial charge Q_{go}/q was varied in the range 0 to 2.2×10^{13} cm^{-2} and set to be positive for *p*MOS structures and negative for *n*MOS structures. These polarities were shown experimentally to have the biggest impact on poly-Si depletion and threshold voltage for *p*MOS and *n*MOS 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 N_{poly} 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*, N_{poly} and V_{fb} 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 *p*MOS devices with $Q_{go}/q = 0$ and $+10^{13}$ cm^{-2}. The *CVC* extracted *EOT*, V_{fb} and N_{poly} 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 *p*MOS 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 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 $Q_{fo}/q = 10^{11}$ cm^{-2}. Such plot may be used to estimate the Q_{go}/q density for a given experimental V_{fb} shift. Example fit to SiO_2 and Al_2O_3 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.

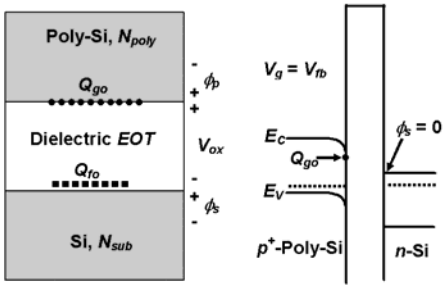

Fig.1 Schematic of poly-Si/dielectric/Si structure. Q_{fo} is the effective fixed oxide charge and Q_{go} is the interfacial charge density at the poly-Si/dielectric interface.

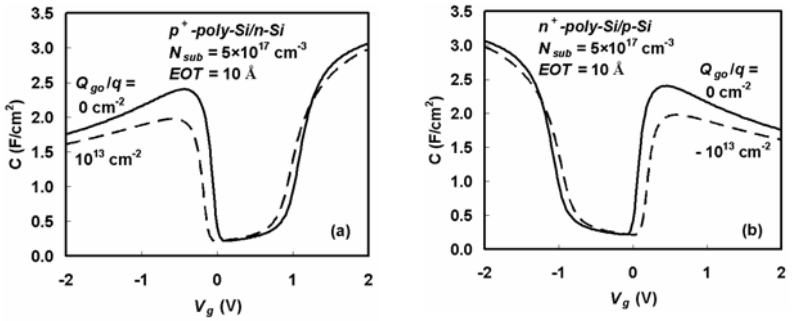

Fig. 2 Representative simulated *C-V* curves for *p*MOS (a) and *n*MOS (b) The poly-Si doping density N_{poly} = 10^{20} cm^{-3}. The presence of Q_{go} at the poly-Si/dielectric interface results in V_{fb} shift and additional poly-Si depletion in strong inversion of p^+-poly-Si/*n*-Si and n^+-poly-Si/*p*-Si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

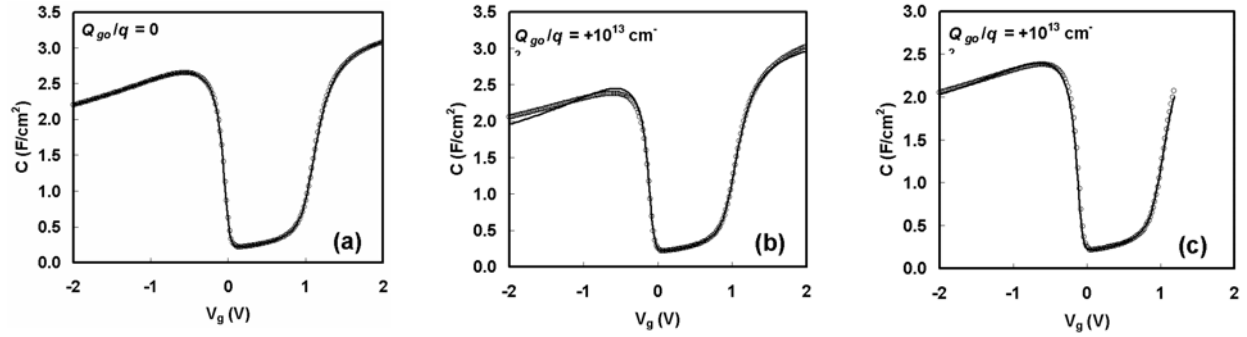

Fig. 3 C-V curves simulated using a model that account for Q_{go} ((1)-(3)) and best fits using *NCSU CVC* tool. (a) Q_{go}/q=0, (b) and (c) fitting bias range from accumulation to inversion and V_{fb} to inversion, respectively, for Q_{go}/q =10^{13} cm^{-2}.

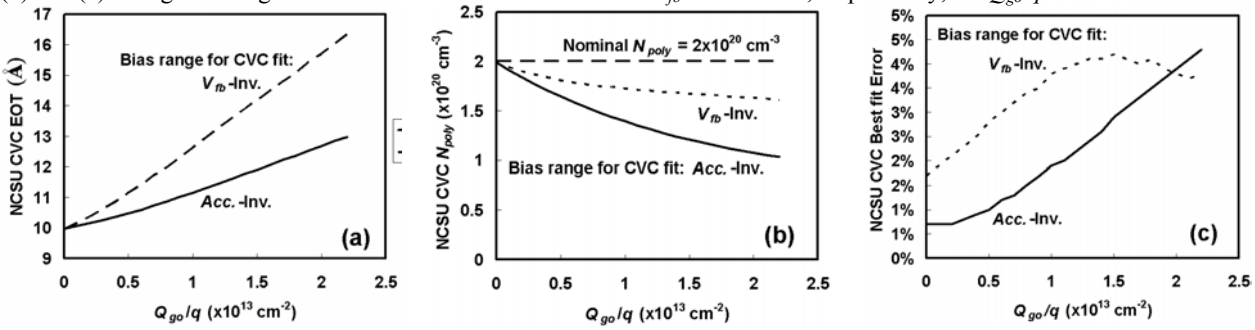

Fig. 4. *NCSU CVC* extracted parameters from simulated *C-V*'s with different Q_{go}/q: (a) *EOT*, (b) N_{poly}, (c) error at best fit.

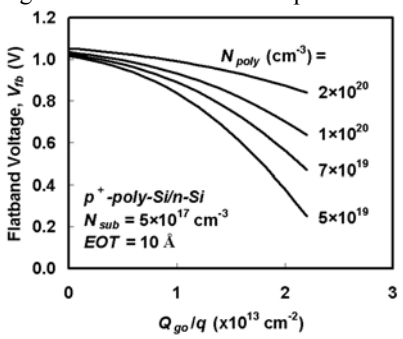

Fig. 5 Simulated V_{fb} vs Q_{go}/q for different nominal N_{poly}.

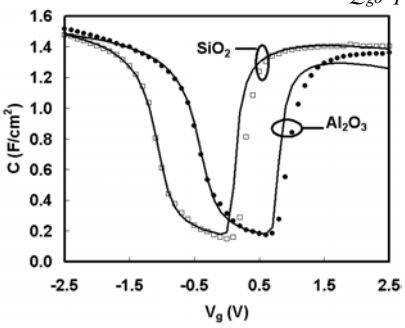

Fig. 6 Data and *CVC* best fits for SiO_2 and Al_2O_3 dielectrics *C-V* data [7].

References

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