FULLY THREE-DIMENSIONAL ANALYSIS OF LEAKAGE CURRENT IN NON-PLANAR OXIDES

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KEYWORDS

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ABSTRACT

We demonstrate the applicability of fully three-dimensional device simulation with the investigation of tunneling currents through oxides and show its benefit for the understanding of physical phenomena especially in the nanometre regime. We compare leakage current measurements from three oxides with different thicknesses (7 nm, 15 nm, and 50 nm), measured by an atomic force microscope (AFM), with simulated Fowler-Nordheim (FN) current distributions and show the necessity of including surface roughness as an essential part of three-dimensional simulation.

INTRODUCTION

During the investigation of gate leakage measurements of oxides with different thicknesses, as shown in Figure 1, it became apparent that taking only the flatband voltage of each of the measured devices into account is insufficient for understanding the measured data. This is shown in Figure 1 where the tunneling currents do not overlap with the theoretical Fowler-Nordheim (FN) curve.

Although the regions indicated in the figure exhibit the characteristics of FN tunneling the curves should overlap for this tunneling mechanism. It was suspected that three-dimensional effects due to surface roughness are at least partially responsible for the observed discrepancy. This spawned interest on how to describe these three-dimensional effects. To investigate the influence of surface roughness on the electrical characteristics of oxides, height data sets obtained from AFM measurements were used as input parameters for modeling. The measured samples provided by *austriamicrosystems* corresponded to the ones subject to the leakage current investigation and were measured at the Institute for Solid State Electronics at the Technical University of Vienna.

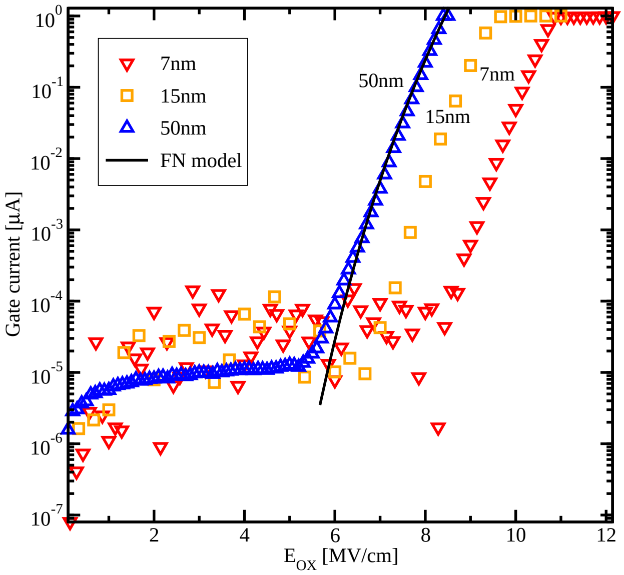

Figure 1: Comparison of the measured oxide tunneling currents. The measurements were performed at *austriamicrosystems*.

AFM MEASUREMENTS

To overcome the difficulties with raw data sets from AFM measurement a pre-processing module (AFM-StructureBuilder: `ASBuilder`) has been developed to correct the raw data sets and to perform the three-dimensional meshing step and contact building.

Raw Data Sets

The raw data set from AFMs measurement are used although some post-processing steps could be done within the measurement software. This is because these steps must be done very accurately and in correlation with the following device simulation steps for a detailed investigation. ASBuilder was developed with these considerations in mind. Figure 2 shows an output of the measurement software.

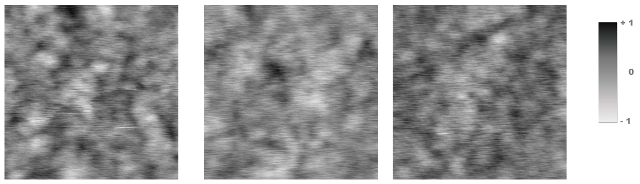

Figure 2: Two-dimensional height distribution of the AFM measurement (left: 7 nm, middle: 15 nm, right: 50 nm).

To enhance the raw data set ASBuilder can filter the data set with different options designed to compensate for different effects encountered during the measurement[1].

- Piezo drift
  Due to heating of the AFM tip during the measurement period the piezo crystal drift results in an z-offset of the measured data set. Within ASBuilder this piezo drift can be recomputed and compensated.
- Fast-scan-line noise
  To reduce fast-scan-line noise a discrete Fourier filter is used to suppress this kind of noise.
- Spike filtering
  To filter noise spikes gauss filters with different kernels can be applied within ASBuilder.

Further Processing of Data Sets

For further processing ASBuilder creates a surface triangulation of the corrected and adjusted height distribution. In order to accomplish this ASBuilder reads in the height distribution data set, corrects the data set and assembles a two-dimensional height distribution matrix. From this matrix an unstructured two-dimensional mesh is generated where the data set is meshed (ASBuilder) with a so called height-map meshing step where the height distribution is triangulated and elevated into three dimensions. The result can be seen in Figure 3.

The histograms of the height distributions presented in Figure 4 show the characteristics of the three different oxides. Here the 7 nm oxide has the flattest distribution which means that the surface roughness is equally distributed between the complete range of 6 nm to 8 nm. The presumably high fluctuations of the 15 and 50 nm oxide are insignificant when compared to the overall thickness of the oxide, while the same does not hold for the 7 nm oxide.

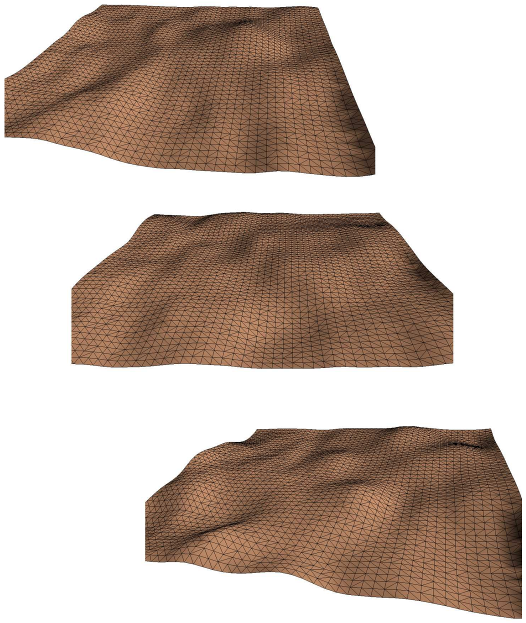

Figure 3: A detailed view of the height distribution (top: 7 nm, middle: 15 nm, bottom: 50 nm).

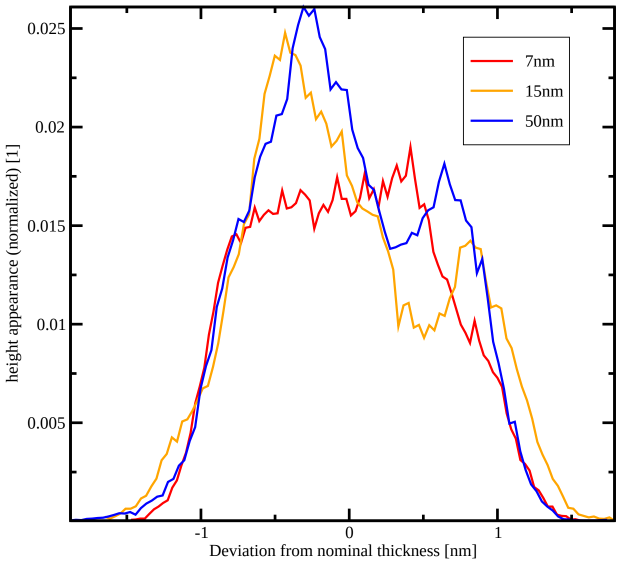

Figure 4: Histograms of the height distributions.

Building the Three-Dimensional Simulation Structures

To investigate oxide reliability in detail the prepared and triangulated surfaces of the oxides are meshed by ASBuilder [2] into a three-dimensional object with a bottom and top metallic contact.

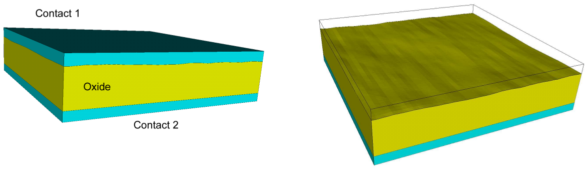

Figure 5: Three-dimensional oxide structure.

With this pre-processing steps of ASBuilder a completely three-dimensional object with the non-planar oxide element and two planar contacts is created which can be used as input data for any existing device simulation software such as Minimos-NT [3] to calculate the electric field distribution required for the modeling of FN tunneling.

SIMULATION METHODOLOGY

After the extensive preparations outlined above several simulation steps need to be performed. First, the electric field distribution is calculated. The results of the three-dimensional electric field calculation are shown in Figure 6 and 7. Figure 6 depicts the absolute values of the electric field, while Figure 7 shows a cut through the three-dimensional simulation domain. Both figures illustrate the influence of the encountered surface roughness on the electric field. The field clearly shows peaks in the regions of thinner oxide inducing heightened electrical stress in these regions.

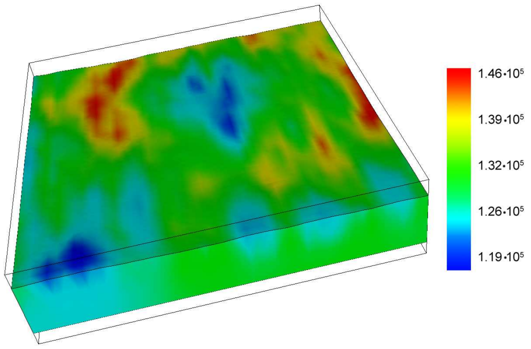

Figure 6: Results of a three-dimensional simulation of the electric field distribution for a $50{\times}50\,\mathrm{nm}^2$ region of a 7 nm oxide. The values of the electric field are in V/cm.

Due to the thickness of the oxides and the strong electric fields the leakage current is modeled as FN tunneling current. It is evaluated using the previously determined electric field distribution. The FN tunneling current is modeled by the well known expression [4, 5]

$$J = a\,|E|^2 \exp\left(-\frac{b}{|E|}\right).$$

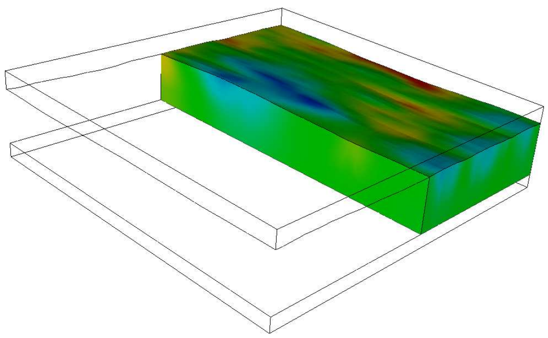

Figure 7: Cut through the simulation domain of a $50{\times}50\,\mathrm{nm}^2$ region of a 7 nm oxide.

The parameters $a = 994.63 \times 10^{-9}\,\mathrm{A/V^2}$ and $b = 2.64 \times 10^{10}\,\mathrm{V/m}$ were calibrated for the non-planar case of each oxide thickness and then used in the subsequent simulations.

COMPARISON OF THE MEASURED LEAKAGE CURRENTS

The area below the 50 nm oxide is ohmically connected to the bulk of the wafer, while the areas corresponding to the thinner oxides are insulated by pn-junctions. The measured structures are schematically presented in Figure 8 for the 50 nm oxide and in Figure 9 for the 7 and 15 nm oxides. This explains the differing noise levels visible in the measurement data (Figure 1) as the measurements of the 7 and 15 nm oxides also include noise from this junction.

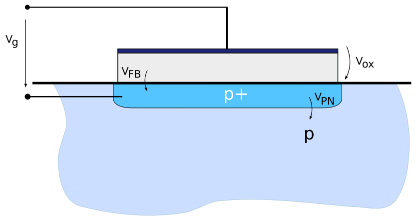

Figure 8: Structure of measurement arrangement (50 nm).

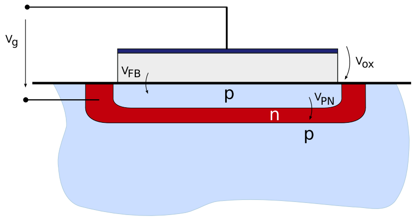

Figure 9: Structure of measurement arrangement (7 nm and 15 nm).

The measured data includes several effects that complicate the analysis. The flatband voltage is one such interference within this measurement. The pn-junctions included in the 7 and 15 nm structures contribute another parasitic effect within the measurement. Both of these effects need to be taken into account in order to enable a correct modeling of the leakage current. Figure 10 shows the influence of the flatband voltage. While the influence on the 50 nm oxide is marginal, there is a significant impact for the thinner oxides. The compensation of the influence of the pn-junctions on the thinner oxides is shown in Figure 11. Again the influence is larger for smaller oxide thicknesses.

$$E'_{\mathrm{ox}} = \frac{V - V_{\mathrm{pn}}}{t_{\mathrm{ox}}}$$

After amending for these effects the measurement curves almost overlap as can be observed in Figure 13. This is an indication of a common mechanism of the leakage current which is readily found in FN tunneling.

SIMULATION RESULTS

After considering the flatband voltage, the pn-junction voltage and the previously determined correction voltages the regions depicted in Figure 1 overlap, as can be seen in Figure 13, and can then be simulated with the FN tunneling model. The result obtained from this simulation is also depicted in Figure 13. The agreement between the measured leakage current and the simulation result is excellent. Using the parameters obtained from the non-planar case, a simulation with planar surfaces is performed as well. This is done by calculating the average height of the oxide from the distribution and assuming a parallel plate capacitor. This corresponds to an effective thickness extracted from CV measurements. The results of this computation is shown in Figure 12. As expected the non-planar curves overlap. The discrepancy between the planar and non-planar case increases with decreasing oxide thickness. This indicates that the relative roughness is responsible for this deviation which, as already stated above, increases as the oxide thickness is reduced. From this it is evident that non-planar effects are increasingly important as oxide thicknesses shrink. From the comparison of the fully three-dimensional and the planar simulations correction voltages can be derived.
The observed tunneling current is not only important for the overall power consumption of devices but also for the reliability of the devices [4], as the tunneling charge carriers are responsible for damaging the oxide and deteriorating the performance of the device.

CONCLUSION

Due to the growing complexity of the structures of modern semiconductor devices and the ongoing shrinking to smaller dimensions, device simulations in two dimensions are no longer sufficient because of dominant three-dimensional effects. This is especially true for oxide properties due to the reduction of oxide thickness to only a few atomic layers.

In particular we have shown that by considering only the effective oxide thickness obtained for instance from CV measurements the estimated FN currents are significantly underestimated due to the non-planarity of the oxide. This effect increases for decreasing oxide thicknesses and has to be considered for oxide reliability considerations.

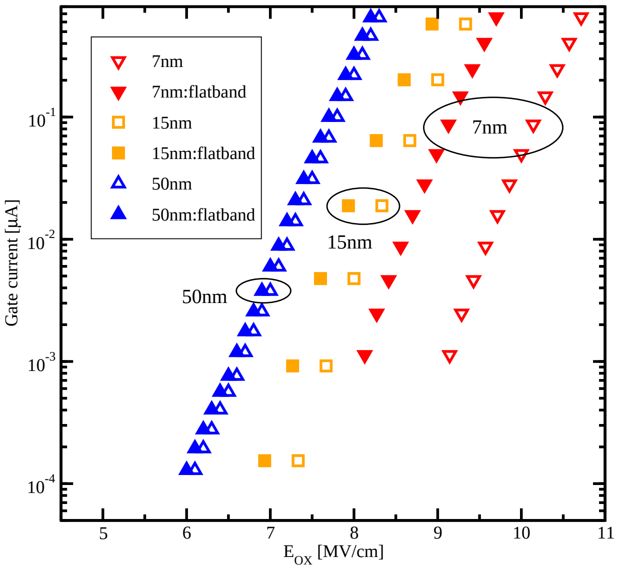

Figure 10: Comparison of the original data set and the corrected set obtained by inclusion of the flatband voltage.

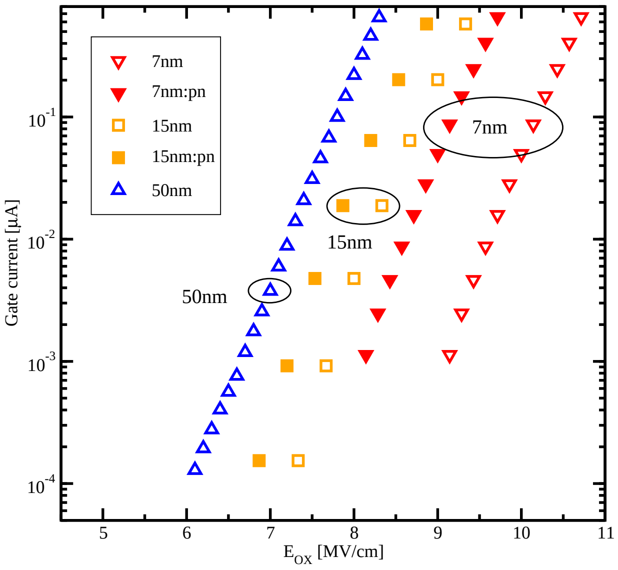

Figure 11: Comparison of the original data set and the data corrected by the pn-junction.

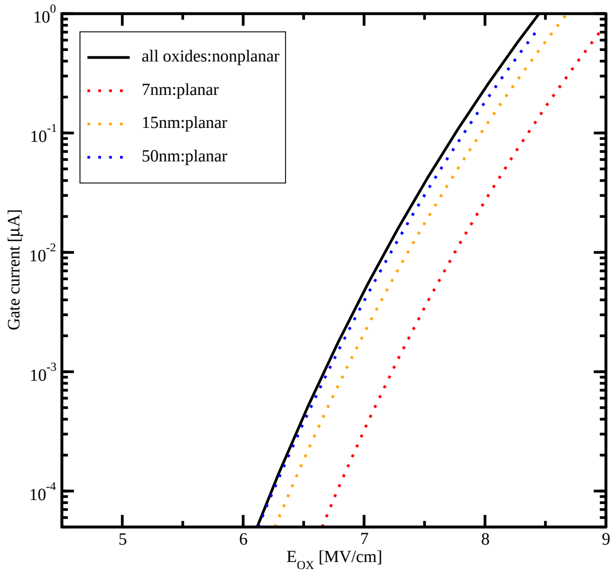

Figure 12: Comparison of the influence of three-dimensional surface roughness effects.

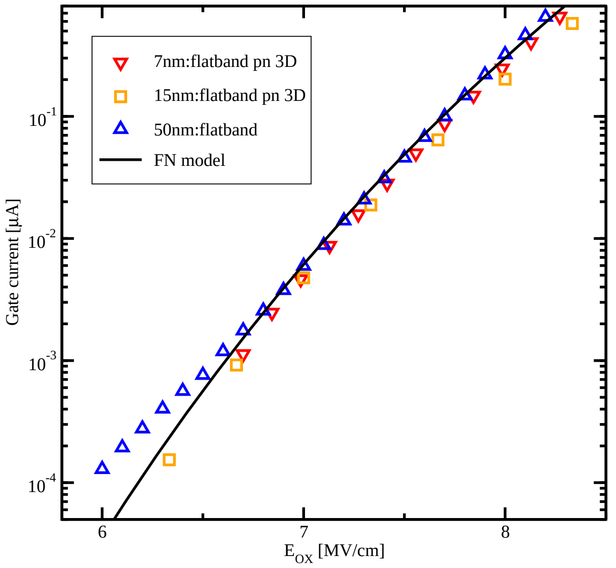

Figure 13: Final simulation compared to corrected measurement data sets.

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BIOGRAPHIES

WOLFGANG BREZNA studied physics at the University of Vienna. In 2005 he received his Ph.D. degree from the Vienna University of Technology, where he is currently working as a postdoctoral research assistant at the Institute of Solid State Electronics. His main research fields are device modification via focused ion beam systems and the development of scanning probe techniques, in particular scanning capacitance microscopy/spectroscopy.

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JÜRGEN SMOLINER received his Ph.D. degree in Physics from the University of Innsbruck in 1988. From 1988 till 1993 he was research assistant at the Walter Schottky Institute of the TU Munich. In 1993 he became assistant professor at the Solid State Electronics Institute and in 1997 associate professor at the TU Vienna. There he is running three scanning probe microscopes, an AFM system, a cryo STM, and a combined cryo STM/AFM. Since 1997 he is heading a group using and developing scanning probe techniques for semiconductor device characterization such as Scanning Capacitance Microscopy and Ballistic Electron Emission Microscopy. He is author and co-author of more than 120 publications.