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Simplified tunnelling current calculation for MOS structures with ultra-thin oxides for conductive atomic force microscopy investigations

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Abstract

As charge tunnelling through thin and ultra-thin silicon dioxide layers is regarded as the driving force for MOS device degradation the determination and characterisation of electrically week spots is of paramount importance for device reliability and failure analysis. Conductive atomic force microscopy (C-AFM) is able to address this issue with a spatial resolution smaller than the expected breakdown spot. For the determination of the electrically active oxide thickness in practice an easy to use model with sufficient accuracy and which is largely independent of the oxide thickness is required. In this work a simplified method is presented that meets these demands. The electrically active oxide thickness is determined by matching of C-AFM voltage–current curves and a tunnelling current model, which is based on an analytical tunnelling current approximation. The model holds for both the Fowler–Nordheim tunnelling and the direct tunnelling regime with one single tunnelling parameter set. The results show good agreement with macroscopic measurements for gate voltages larger than approximately 0.5–1 V, and with microscopic C-AFM measurements. For this reason arbitrary oxides in the DT and the FNT regime may be analysed with high lateral resolution by C-AFM, without the need of a preselection of the tunnelling regime to be addressed.

Keywords: C-AFM; MOS; Tunnelling; Ultra-thin oxides

1. Introduction

Charge transport through the SiO_2 (oxide) layer is regarded as the driving force for oxide degradation and dielectric breakdown [1] in MOS structures. In this context thickness variations of gate oxides or electrically week spots have become increasingly critical [2] as the gate dielectric is reduced to, for example, less than 2 nm for the current 130 nm technology. Macroscopic MOS capacitors and MOS devices are widely used to determine the conductive properties of the dielectric [3]. These analyses give generalised information but are unable to provide details concerning the distribution of local oxide thinning or microscopic electrically weak sites [2,4] because dielectric breakdown is considered to be an extremely localised phenomenon (10^{-14} to 10^{-12} cm^2) [5]. Conductive atomic force microscopy (C-AFM) has been reported [2,6–11] to be a suitable tool to address this issue. With C-AFM it is possible to determine the electrically active oxide thickness by superposition of current–voltage measurements (IV-spectroscopy) with a tunnelling current model [6–9] and to derive oxide thickness maps by interpretation of tunnelling current maps for a fixed stress voltage [8]. For this purpose in earlier studies [6–9] the Fowler–Nordheim tunnelling (FNT) theory [12–14] was applied. However, as oxide thickness has become smaller than 3 nm, the FNT theory is not sufficient

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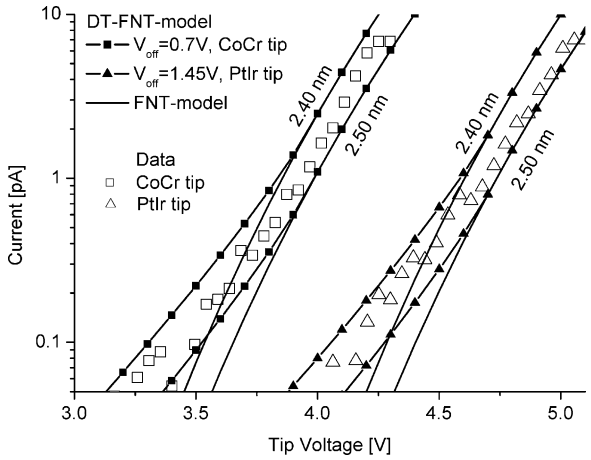

Fig. 1. Measured C-AFM IV-spectroscopy curves (hollow symbols) correlated with the combined DT-FNT model (Eq. (5)) (solid symbols) and the single FNT model (Eq. (1)) (line). The data has been recorded with CoCr coated and PtIr coated tips. The different coating material work functions caused different offset voltages for identical oxide thickness, which are stated in the legend.

to describe the tunnelling current. This effect may be seen in Fig. 1 for C-AFM measurements and in Fig. 2 for conventional macroscopic tests. In both figures the tunnelling current is changed gradually by thinner oxides and decreasing bias, from the FNT regime into the direct tunnelling (DT) regime [15–25]. In failure analysis (FA) the task of C-AFM is to determine material parameters of failed devices to establish if these differ significantly from the target values. Primarily, oxide thickness and oxide homogeneity are often widely unknown and thus a preselection of the tunnelling regime to be addressed may be misleading. For the stated reasons the critical feature of a tunnelling current model for interpretation of C-AFM measurements is that it is able to address both the DT and the FNT regime in a continuous manner. Furthermore, it must produce repeatable results with reasonable accuracy in the voltage and current range addressed, and must be applicable over a wide range of material parameters. It must necessarily be easy to use in practical application in failure analysis.

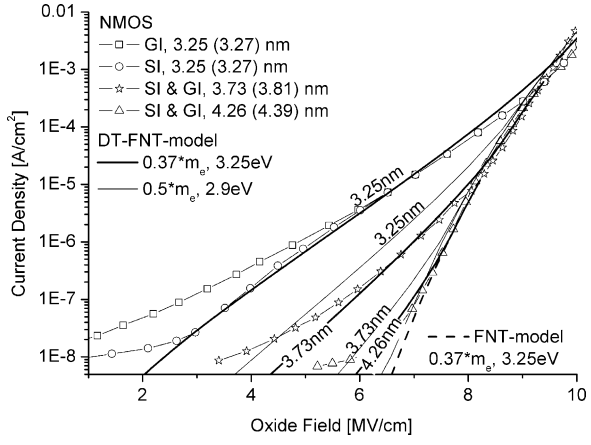

Fig. 2. Measured [26] (hollow symbols) and calculated (Eq. (5)) tunnelling current density (lines) as a function of F_{ox} for NMOS structures in substrate injection (SI, inversion) and (GI, accumulation). F_{ox} was calculated using the nominal oxide thickness stated in the legend, which was determined by quantum-interference technique [26]. The value in brackets was obtained for full quantum-mechanical treatment [26]. In the FNT regime all curves overlay while in the DT regime $m_{ox} = 0.37m_e$ and $\phi_B = 3.25$ eV (thick lines) yielded improved results compared to $m_{ox} = 0.5m_e$ and $\phi_B = 2.9$ eV (thin lines) for identical oxide thickness.

In this work a method is presented, which is based on a formula published by Schuegraf and Hu [16], that satisfies these demands. In combination with the single parameter set derived in this study, it is possible to determine the oxide thickness by IV-spectroscopy without the need to distinguish between DT and FNT regime.

2. Tunnelling current calculation

In MOS structures for oxide voltage (V_{ox}) larger than (ϕ_B/q), where (ϕ_B) represents the energy barrier height between the emitting electrode and the oxide and (q) equates the electron charge, the FNT theory [12–14] applies while for $V_{ox} < \phi_B/q$ DT occurs [15–25]. For macroscopic MOS structures at practical measurement conditions FNT is dominant above approximately 5 nm oxide thickness while DT is prevailing below 3 nm. For intermediate values both phenomena may be observed (Figs. 2 and 4). In the case of C-AFM measurements a conductive tip is applied to an oxide surface and a MOS structure is built by conductive tip and sample, where the tip plays the role of the gate electrode. The effective electron emission area of this system is in the order of only some tens to a few hundred square nanometers [6–9]. For this reason FNT behaviour may be observed for C-AFM until approximately 2.4 nm (Fig. 1) because higher bias is necessary to drive a measurable current.

2.1. Fowler–Nordheim tunnelling

Even though the FNT theory (Eq. (1)) has been developed for metal electrodes in vacuum [12], it is also applicable for MOS structures [14]:

$$J = AF_{ox}^2 \exp\left(\frac{-B}{F_{ox}}\right) \tag{1}$$

$$A\,(\mathrm{A/V^2}) = \frac{q^3}{16\pi^2\hbar}\frac{m_e}{m_{ox}}\frac{1}{\phi_B} = 1.54\times10^{-6}\frac{m_e}{m_{ox}}\frac{1}{\phi_B} \tag{2}$$

$$B\,(\mathrm{V/cm}) = \frac{4}{3}\frac{\sqrt{2m_{ox}}}{q\hbar}\phi_B^{3/2} = 6.83\times10^7\left(\frac{m_{ox}}{m_e}\right)^{1/2}\phi_B^{3/2} \tag{3}$$

In Eq. (1) J is the tunnelling current density, F_{ox} the electrical field across the oxide and thus the ratio of the effective oxide voltage (V_{ox}) and the electrically active oxide thickness (d_{ox}).