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Scanning spreading resistance microscopy (SSRM) 2d carrier profiling for ultra-shallow junction characterization in deep-submicron technologies

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Abstract

This work presents the recent progress in SSRM capabilities highlighting simultaneous performances in terms of sensitivity (<10%), spatial resolution (1–3 nm), dopant gradient resolution (1–2 nm/decade) and quantification accuracy (20–30%). The latter is illustrated through the analysis of different carrier profiling applications, i.e. the calibration of process simulations for a 90 nm n-MOS technology, the determination of the impact of nitridation on the lateral diffusion in a 40 nm n-MOS technology, the study of activation and diffusion problems in SPER-anneals of shallow implants, the observation of stress-induced diffusion mechanisms in the vicinity of shallow trench isolations (STI) and the study of diffusion and mobility mechanisms in SiGe MOS structures. Favorable comparisons with SCM and STM are also presented and do illustrate the unique capability of the SSRM technique.

Keywords: AFM; SSRM; Microscopy; Two-dimensional; Carrier-profile; Quantification; Spreading resistance

1. Introduction

Due to downscaling, the electrical characteristics of the new devices are highly dependent on the exact distribution of the carriers and concepts like LDD/HDD structures, pocket and halo implants or channel profile engineering are introduced to control precisely the carrier distribution. The physics is also more and more complex and has evolved from a one-dimensional approximation to a two-dimensional description. Finally, TCAD process simulators, which have followed the physics evolution and have shifted from a one-dimensional to a two-dimensional description, suffer from a lack in calibration. They are particularly inefficient for the new activation mechanisms (SPER, flash and laser annealing, ...) that also introduce new diffusion and activation problems. For all those reasons is a real two-dimensional electrical profiling technique more than necessary.

Scanning spreading resistance microscopy (SSRM) is an electrical characterization technique, based on atomic force microscopy (AFM), which has been conceived and developed at IMEC in the past years to probe the two-dimensional resistivity (and carrier) distribution in semiconductor devices [1,2]. The SSRM concept is in fact born from the motivation to extend the capabilities of the spreading resistance probe technique (SRP) by replacing the large SRP probes (1 μm) with a small probe (radius about 10 nm) mounted on an AFM system. The idea was to allow direct measurements on the sample cross-sections (in order to avoid the beveling related carrier-spilling effects) as well as two-dimensional carrier profiling without special test structures. In SSRM, a hard conductive AFM probe is scanned in contact mode across the sample, while a d.c. bias is applied between a back-contact on the back-side of the sample and the tip. The resulting current is measured using a logarithmic current amplifier providing a typical range of 10 pA to 0.1 mA. The main characteristic of SSRM is that the technique uses a high force (above the μN) to realize an intimate contact between the probe and the silicon sample such that spreading resistance dominates the contact resistance. Clarysse et al. [3] have established that for such pressures, the probe punches through the silicon oxide and the underlying silicon undergoes a plastic deformation and phase transformation. Note that recent publications have been dedicated to the detailed analysis of the SSRM contact [4,5].

Experimental and modeling improvements in SSRM [6] as well as the advent of new generations of full diamond molded probes [7,8] have put the SSRM technique inline with the stringent ITRS requirements for two-dimensional dopant profiling (see Table 1). In particular, the SSRM combination of high spatial resolution and good sensitivity (that is directly linked to the concentration precision) is unique. At the moment, SSRM is

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Table 1
Comparison of SSRM capabilities with the ITRS requirements

	SSRM 1998	SSRM 2004	ITRS 2005	ITRS 2010	ITRS 2016
Lateral/vertcical steepness of dopant profile (nm/decade)	NA	1–2	4.25	2.7	1.6
Lateral/depth spatial resolution for 2D dopant profile (nm)	10–20	1–3	2	2	1
Dopant profile concentration precision across concentration range (%)	20	5–10	4	2	2
Dynamic range (at/cm^3)	10^{15}–10^{20}	10^{15}–10^{20}	10^{14}–10^{21}	10^{14}–10^{21}	10^{14}–10^{21}

therefore a powerful and inimitable tool for the analysis of existing technologies and the support in development of new technologies where mechanisms as lateral diffusion, stress induced diffusion or partial activation have an increasing importance.

2. Applications

2.1. Calibration of process simulators for 90 nm n-MOSFETs

Transistors from a 90 nm node technology with gate sizes ranging from 500 nm down to 70 nm have been measured and the SSRM results are compared with the results from a process simulator, which was initially run using a default set of parameters (Fig. 1). The results emphasize the ability of SSRM to probe finer details of the 2D-carrier distribution within the channel area, which result from the halo and V_t-adjust implants. Small concentrations variations (<25%) within the channel as well as in-between structures with different gate sizes can be observed. The change in 2D-carrier profile with gate size can clearly be observed illustrating the increasing overlap of the pocket implants with decreasing gate size.

Comparisons of the lateral extent of the halo-profiles between SSRM and simulations indicate that the simulations underestimate the lateral width of the halo-profiles (while the vertical depth is similar to the SSRM results). Quantitative comparisons of channel profiles taken on large structures also indicate a difference in absolute concentration of around 25% between SSRM and simulations (see Fig. 2). The deficiency of the simulations becomes also apparent when comparing experimental and simulation device characteristics (in this case the V_t-roll off Fig. 3 (left)). An improvement can be obtained when using the SSRM results i.e. adapting the simulations to produce a higher lateral diffusion and decreased channel concentration. As shown in Fig. 3 (right) (representing the relative V_t variation between 0.5 and 1 μm gate size before and after taking into account the

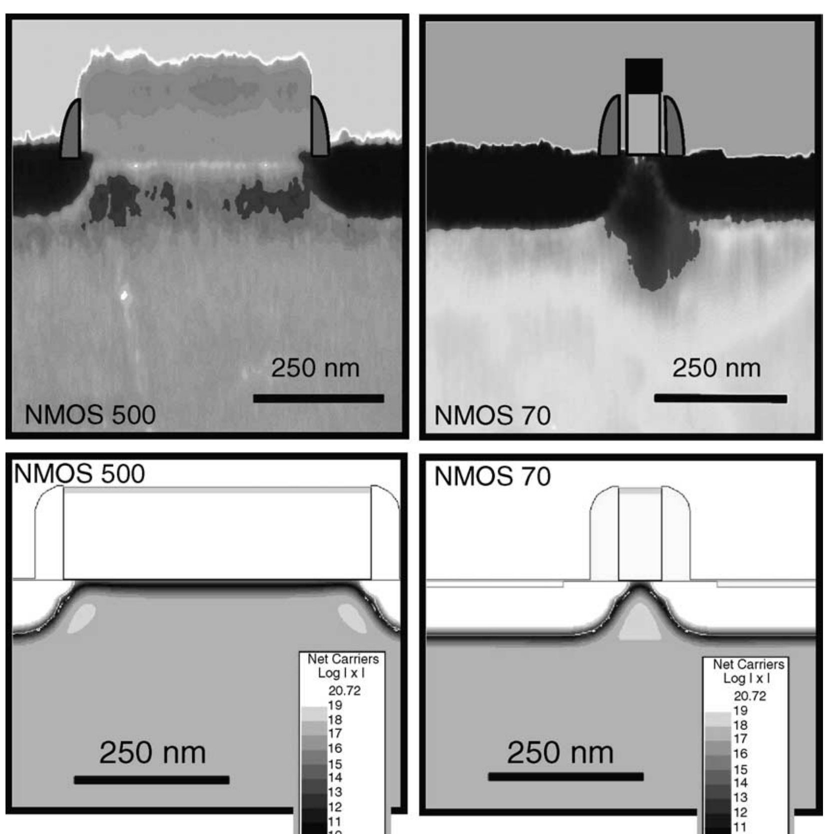

Fig. 1. SSRM measurement (top, black is more conductive) and simulation (bottom, white is more conductive) for 500 and 70 nm n-MOS structures. Separation of the halo pockets for 500 nm gate size is visible for simulation and measurement.