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***Abstract*— The reduction of the contact resistance R_C is one of the most challenging issues related to the miniaturisation of advanced MOSFET architectures, including FDSOI technology (Fully Depleted Silicon-On-Insulator). R_C strongly depends on the active dopant concentration at the semiconductor/salicide interface. It is therefore essential that electrical activation at different depths within a doped layer is reliably determined to optimise the fabrication processes. In this paper, we firstly present a Differential Hall Effect (DHE) method which allows measuring the active dopant concentration profile close to the surface with nm resolution for ultra-shallow doped $Si_{1-x}Ge_x$ and Si layers. Then, we present DHE measurements made on junctions processed with advanced techniques, including nsec LTA and msec DSA anneals.**

Keywords*– *FDSOI, contact resistance, shallow junctions, Differential Hall Effect

I. INTRODUCTION

The research efforts made throughout the last decades have made it possible to keep the momentum for a continuous miniaturization of electronics devices. For instance, the bulk planar transistor limitations have been overcome thanks to the diversification of the device architecture, with the actual spectrum going from enhanced planar architectures like FDSOI **[1]** to 3D transistors like TriGate FinFETs or gate-all-around NWFETs. Despite their differences, some technological issues, such as the reduction of the access resistance, still represent a common challenge for all of them. According to theory, the increase of the active dopant concentration at the semiconductor/silicide interface is a strong lever for access resistance reduction (eq. (1)):

$$\rho_{Sal,SC} = \rho_{Sal,SC_0}.exp\left(\frac{2\phi_B}{\hbar}\sqrt{\frac{\varepsilon_S m^*}{N}}\right) \propto \frac{\phi_B}{\sqrt{N}} \qquad (1)$$

Several techniques including dopant segregation and pre-amorphisation have been proposed to this purpose. Further optimisation of the doping processes (or improvement of the TCAD models calibration), make it therefore necessary to reliably characterize dopant activation at the surface of the doped layers.

Hall effect has been used for years to characterize semiconductors providing the active dose N, the sheet resistance R_S and the carrier mobility μ. However, due to current flowing in the whole layer, only average values are measured. Differential Hall Effect (DHE) has therefore been proposed in order to extract depth depending values of these parameters. This method is based on the iteration of oxidation/etch cycles based either on anodic or native oxidation processes, with the etch rate determining the depth resolution. DHE has been successfully demonstrated for pure Si and Ge; however its application to SiGe is far more challenging due to the different oxidation rates of these two species.

In this paper, we present a DHE method allowing to precisely evaluate these parameters for both Si and SiGe materials. The method is presented in section II and then applied to test structures fabricated using advanced processes (section III).

II. DIFFERENTIAL HALL EFFECT METHOD

A. *Ecthing processes*

For SiGe, we use a one-step chemistry based on the SC1 solution that simultaneously oxidizes and etches both Si and Ge **[3] [4].** For Si, a two-step process consisting in controlled ambient air oxidation followed by HF oxide stripping and ethanol rinsing is used **[5]**. Both processes allow reaching sub-1nm etching resolution with negligible surface roughness and, for SiGe, stoichiometry conservation. All these characteristics have been determined by AFM, XRD, TEM and ellipsometry and are summarized in **Tab. 1**.

B. *Electrical measurements*

Electrical measurements are performed on optimized greek-cross Van der Pauw structures (1.8 x 1.8 cm^2). A dedicated o-ring cell has been designed to protect the metallic peripheral contacts during etch. After a sequence of oxidation/etch and measurements cycles, it

Characteristics	Si	$Si_{1-x}Ge_x$
Chemistry	HF(5%) + Ethanol	$NH_4OH:H_2O_2:H_2O$ (1:1:5)
Mechanism	Oxidation then stripping **(2 steps)**	Oxidation and dissolution **(1 step)**
Surface	Low roughness (~0,2nm)	Low roughness (~0,1nm)
Etchrate	~ 1 nm / cycle	~ 0,5 – 1 nm / cycle
Stoechiometry	-	Preserved

Tab. 1: Summary of main features of Si and SiGe etching chemistries.

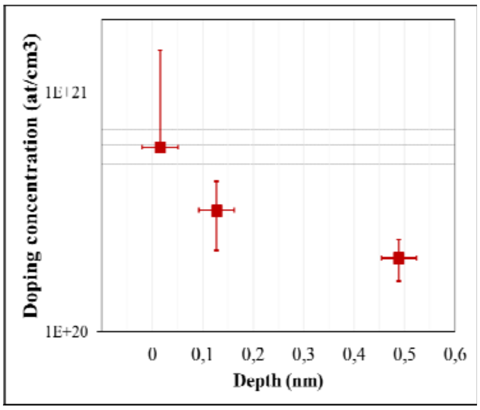

Fig. 1: Depth distribution of the active dopant concentration as determined by Differential Hall effect measurements from the SiGeOI sample implanted with Boron and laser annealed at an energy density of 0.68 J/cm^2.

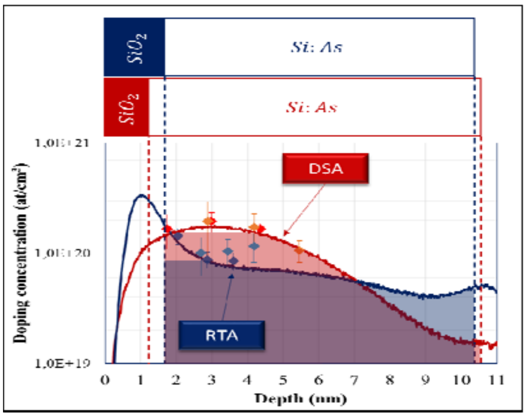

Fig. 2: Depth distribution of active dopant concentration for DSA and RTA processes measured by DHE **(colored dots)** compared to their respective SIMS **(colored lines)** from the 11 nm SOI samples implanted with arsenic at the same dose (10^{14}at/cm²). Colored areas in the graph correspond to the active dose. Diagrams above graph zone represent the layers dimensions measured by ellipsometry.

is finally possible to extract the dopant concentration profile as a function of depth, taking into account the predetermined Hall scattering factor (~0.75 for Si and ~0.4 for SiGe **[5] [6]** for *p-type* doping).

III. Application of DHE procedure to samples fabricated with advanced techniques

A. 6nm SiGeOI layers doped by Ion Implantation and nanosecond LTA (Laser Thermal Annealing)

In the designed process, *n-type* and *p-type* dopants were implanted in a pre-amorphised SiGe layer obtained by Ge^+ implant. LTA was achieved using a SCREEN-LASSE XeCl excimer laser (λ = 308 nm) with energy densities ranging from 0.65 to 0.79 J/cm^2. Although the investigated doping process is at a preliminary stage, and considering the difficulty in controlling the sharp transition between a "no melt" and a "full melt" condition for such ultrathin layers, our DHE investigations allow to conclude that a doping process based on nanosecond laser annealing can be successfully applied to ultrathin SiGeOI layers of ~6 nm thickness, with achieved active dopant concentrations at the surface well above $1x10^{20}$ cm^{-3} for annealing conditions below the threshold energy (0.68 J/cm², **Fig. 1**). This is a promising result in view of improving contact resistivity in source/drain regions of advanced devices.

B. 11nm SOI layers doped by Ion Implantation and annealed by spike-RTA or msec DSA methods

We also characterised 11nm-thick arsenic doped SOI layers processed either with RTA annealing (Rapid Thermal Annealing) or with msec DSA laser annealing (Dynamic Surface Annealing). For the same implanted dose, conventional Hall effect measurements indicate that a higher active dopant fraction is achieved by DSA compared to RTA. Our DHE analysis reinforced this result by showing that a higher active dopant concentration is achieved at the surface by DSA (cf. **Fig. 2**), confirming the interest for DSA as an efficient solution for contact resistance reduction.

IV. Conclusion

We presented a DHE method for the investigation of dopant activation in ultra-thin Si and SiGe layers. We demonstrated the reliability of our process in terms of depth resolution, surface roughness and stoichiometry. The DHE method is applied to samples fabricated by advanced doping techniques. Fast anneals as LTA and DSA are confirmed as very efficient activation processes to achieve the high surface dopant concentrations that are required for contact resistance optimisation.

Acknowledgments

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