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Selective epitaxial p-(Si)Ge Source-Drain Contacts: Low Contact Resistivity (~ $1.5x10^{-9}$ Ω.cm^2) by Optimizing Strain and Doping Concentration

Clement Porret[1], Yan Hua Huang[1-3], Gianluca Rengo[1,3], Hao Yu[1], Marc Schaekers[1], Jean-Luc Everaert[1], Marc Heyns[1,3], Anurag Vohra[1,3], Andriy Hikavyy[1], Erik Rosseel[1], Robert Langer[1] and Roger Loo[1]

[1] Imec vzw
Kapeldreef 75, B-3001 Leuven, Belgium
Phone: +32-1628-3541 E-mail: Clement.Porret@imec.be
[2] National Tsing Hua University
No. 101, Section 2, Kuang-Fu Road, Hsinchu 300, Taiwan 30013, R.O.C.
[3] K.U. Leuven
Celestijnenlaan 200D, B-3001 Leuven, Belgium

Abstract

We present a comprehensive study of Ti / (Si)Ge:B contacts formed using in situ doped materials, without any post epitaxy anneal. We specifically emphasize the importance of strain in SiGe:B grown on Si and demonstrate contact resistivities down to $2.3x10^{-9}$ Ω.cm^2. For Ge, we focus on the impact of doping and reach contact resistivities values as low as $1.5x10^{-9}$ Ω.cm^2.

1. Introduction

The quest for performance through miniaturization has led the microelectronics industry to consider transistors with tiny features. However, reports on designs considering aggressive critical dimensions (CD) indicate limitations in device performance due to parasitics [1]. One of the main detractors lies in the raise in series resistance at low CD. This deterioration can be alleviated by precisely engineering the band structure in the contact region. This requires optimizing the source-drain (S/D) materials and their subsequent processing. To meet the requirements for sub 7 nm nodes, the metal-to-S/D contact resistivity (ρ_c) should be lowered down to ≤ $1x10^{-9}$ Ω.cm^2 [2].

Highly B-doped SiGe stressors are widely used as S/D for pMOS Si devices [3-7] as they enable high doping, enhanced channel mobilities and offer band gap modulation opportunities. The main focus presently goes for $Si_{1-x}Ge_x$ with high Ge contents (40% ≤ x ≤ 75%) [4,7]. As recently shown experimentally [4] and theoretically [5], a precise tuning of Ge content allows for a decrease in ρ_c down to the desired range. Moreover, simulations presented in [5] indicate benefits from strain engineering in SiGe:B. Unfortunately, to the best of authors' knowledge, there was no systematic experimental study of the impact of strain on ρ_c published to date.

In this contribution, we analyze Ti / (Si)Ge:B contacts fabricated using device-compatible epitaxial growth conditions. We discuss how strain in the S/D layer affects contact resistivity and try to understand the mechanisms responsible for variations in ρ_c. For SiGe:B, increasing the B level above the solubility limit results in the incorporation of non-substitutional B, which reduces the critical thickness for layer relaxation. We therefore also studied the contact resistivity of Ge:B epitaxially grown on strain-relaxed Ge virtual substrates, as this allows to learn how ρ_c depends on doping without any influence of relaxation issues.

2. Experimental details

The layers discussed in this work were prepared in a 300 mm ASM Intrepid™ reduced-pressure chemical vapor deposition reactor. $Si_{0.5}Ge_{0.5}$:B layers with different thicknesses ($t_{SiGe:B}$) were grown on n-Si(001) using SiH_2Cl_2 and GeH_4. B_2H_6 was used for p-type doping and HCl added to the growth chemistry to achieve selective growth. Full selectivity was confirmed on Si oxide and nitride surfaces. B-doping was adjusted to obtain the highest carrier concentration without compromising surface morphology. Using selected epi conditions, a B chemical concentration of $4x10^{20}$ cm^{-3} was determined by secondary ion mass spectroscopy (SIMS). Dopants were confirmed to be ~ 100% active with micro Hall effect measurements. Ge:B was deposited on n-Ge/Si(001) following the cyclic deposition-etch (CDE) procedure described in [8] and applied to Ge gate-all-around p-FET presented in [9]. The growth was performed at low temperature (< 350°C) using Ge_2H_6 and B_2H_6. Cl_2 was employed as a selective etchant to guarantee process selectivity. Growth conditions were varied to modulate the B chemical concentration from $6.2x10^{20}$ cm^{-3} to $2.7x10^{21}$ cm^{-3}. Contact resistivities were extracted from multi-ring circular transmission line model structures using the fabrication scheme described in [10,11].

3. Results and discussion

The thin SiGe:B (≤ 35 nm) layers studied in this work exhibit smooth surfaces, with scattered-light intensities (haze) values lower than 2.5 ppm (Fig. 1).

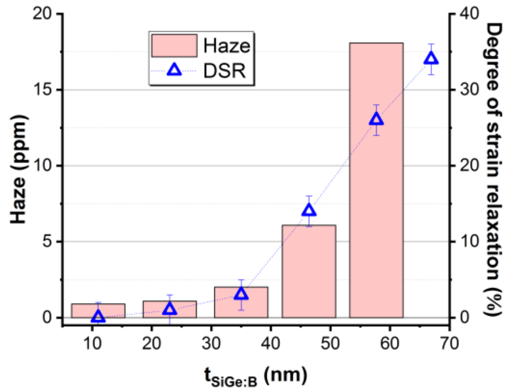

Fig. 1 Average haze intensities (bars) recorded as a function of SiGe thickness and corresponding degree of strain relaxation (triangles).

For thicker SiGe:B (≥ 46 nm), the haze signal increases rapidly, indicative of surface roughening due to material relaxation, confirmed by atomic force microscopy and X-ray diffraction measurements (not shown here). The degree of strain relaxation (DSR), extracted from asymmetric (113) reciprocal space maps, is plotted in Fig. 1. for comparison.

Fig. 2. shows how the electrical properties vary with layer thickness. When increasing $t_{SiGe:B}$, the layer resistivity (ρ) first decreases and reaches a minimum value for $t_{SiGe:B}$ = 23 nm . For $t_{SiGe:B} \geq 35$ nm, ρ increases monotonically but stays below 0.5 mΩ.cm. Correspondingly, ρ_c reaches a minimum of 2.3x10^{-9} Ω.cm^2 for 23 nm SiGe, and increases for higher $t_{SiGe:B}$. These results can be assigned either to (i) a depletion of carriers in the S/D -low $t_{SiGe:B}$-, (ii) local changes in the band structure or (iii) variations in metal / semiconductor interface roughness, both (ii) and (iii) being due to SiGe:B relaxation. This indicates that optimizing $t_{SiGe:B}$ to preserve strain in the material is important to achieve low contact resistivities.

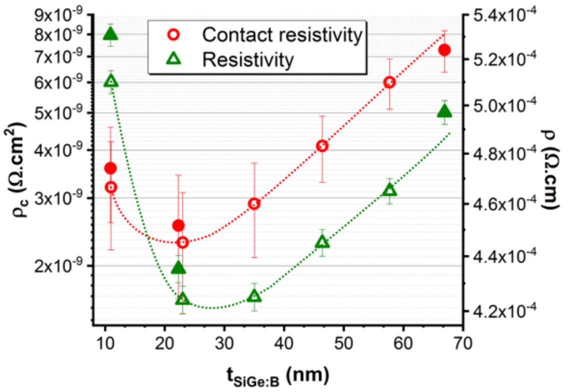

Fig. 2 Resistivity (as-grown layers, triangles) and contact resistivity (circles) extracted as a function of SiGe:B layer thickness. Solid and open symbols correspond to different experiments and illustrate process reproducibility. Dotted lines are guides for the eye.

Next, we evaluate the impact of post metal anneals (PMA) on contact properties. Different PMA were applied to 23 nm SiGe:B contacted with 5 nm Ti + 3 nm TiN. All PMA were performed for 1 min in N_2. Only the temperature was varied. Fig. 3. summarizes the ρ_c values obtained using PMA from 450 to 650ºC. We do not observe any benefit from the PMA. Contact resistivities remain below 3x10^{-9} Ω.cm^2 for temperatures up to 500ºC, demonstrating the thermal stability of the prepared contacts up to that temperature. For PMA at 550ºC and above, a fast increase in ρ_c up to the 10^{-8} Ω.cm^2 range is observed, attributed to the formation of Ti(SiGe)$_2$ grains [12].

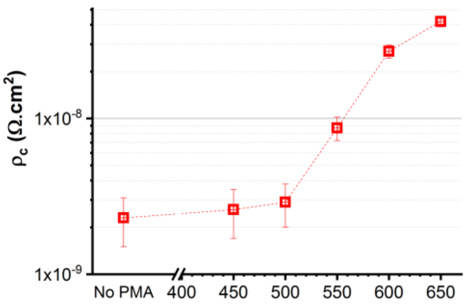

Fig. 3 Contact resistivities measured for different PMA temperatures.

We finally investigate Ti / Ge:B contacts, considering B-doping as the main parameter affecting ρ_c. As can be seen in Fig. 4, ρ_c values as low as 1.5x10^{-9} Ω.cm^2 are achieved with increasing the active B concentration ($[B]_{active}$) up to a value of 6.1E20 cm^{-3}. However, the resistivity of the epi layer follows the opposite trend and increases with increasing $[B]_{active}$. A compromise therefore needs to be found to minimize the overall device resistance.

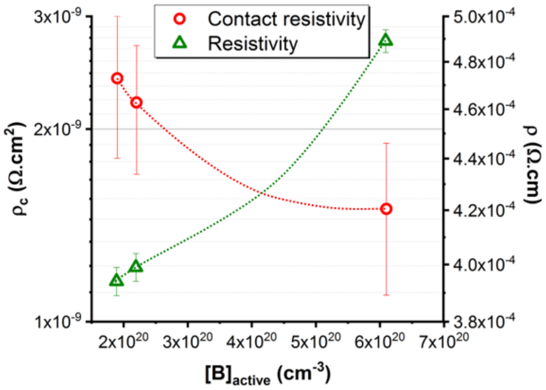

Fig. 4 Resistivity (as-grown layers, triangles) and contact resistivity (circles) extracted as a function of doping concentration in Ge:B.

4. Conclusions

We discuss how the Ti / SiGe:B contact resistivity is affected by SiGe thickness and correlate the performance with the strain in the epitaxially grown material. We identify optimal conditions where SiGe:B is kept fully strained and assign the increase in ρ_c with increasing layer relaxation to modifications of the band structure. For Ti / Ge:B contacts, contact resistivity values as low as 1.5x10^{-9} Ω.cm^2 are extracted for highly B-doped layers. However, this comes with an increase in S/D resistivity. This exercise is an important step towards achieving low contact resistivities in a reliable way, as it illustrates the high sensitivity of contacts when approaching the low 1x10^{-9} Ω.cm^2 contact resistivity regime.

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