Characterization of Doping and Activation Processes Using Differential Hall Effect Metrology (DHEM)

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Differential Hall Effect Metrology (DHEM) technique was used to study dopant activation in n-Si and p-SiGe materials. n-type Si samples were prepared by P ion implantation followed by RTA at temperatures ranging from 750ºC to 950ºC. Junction depth and dopant activation through the layers were correlated with process parameters. Using DHEM mobility profiles, a correlation was also established between the EOR defect location and their elimination through high temperature annealing. DHEM resistivity depth profile displayed increased resistivity in the surface region of B-doped SiGe (50%) epi layer. This electrical behavior is in excellent agreement with expected reduction in B incorporation as strain-relaxation occurs towards the free surface. These results demonstrate prime importance of DHEM capabilities for engineering of advanced contacts.

Introduction

As advanced CMOS technology scaling goes beyond 7nm node, contact resistivity becomes an important factor influencing device performance. Approaches to reduce contact resistivity involve advanced doping techniques that yield very high degree of dopant activation in the semiconductor layers at the source and drain regions. These approaches include in-situ heavily doped epi layer development and ion implantation followed by advanced annealing techniques. Irrespective of the approach used in wafer processing, accurate analysis of dopant activation within the top few nanometers of the surface is of critical importance to be able to understand the effectiveness of such processes on improving contact resistivity. Similarly, correlation of mobility depth profiles to defectivity in the layers helps one to understand how process variables may affect the ultimate electrical properties of the semiconductor layers. Differential Hall Effect Metrology (DHEM) is a unique method that can provide mobility and active dopant depth profiles through semiconductor layers at sub-nm resolution. Superior depth resolution of DHEM allows collection of dopant activation data within 4nm of the top surface. The method employs electrochemical means to reduce the electrically active thickness of a semiconductor film and determines the sheet resistance and mobility of the thinned down layer using Van der Pauw/Hall effect type measurements (1). By repeating the steps of thickness reduction and electrical characterization, a depth profile of the desired electrical property can be obtained. Dopant activation in n-type Ge layers was previously studied using this technique (2). In this contribution we demonstrate the capabilities of DHEM through measurements on n-Si and p-SiGe films.

Experimental Details, Results and Discussion

Silicon Samples

The sample characterized was a p-type Si wafer ion implanted with P (10keV, 2E15cm^{-2}). After implantation, the wafer was coated with positive photoresist, exposed, and developed in order to define a cross-shaped Van der Pauw structure. After formation of the DHEM test pattern mesa using dry etching, wafer pieces were processed by rapid thermal anneal (RTA) at 750 °C, 850 °C, and 950°C in nitrogen ambient for 30 seconds. After annealing, samples were subjected to a negative photoresist process in order to open contact windows at the ends of the cross arms. After the exposure and development, native oxide was removed from the contact windows and metallic contacts were evaporated. This etching process was not applied to the test region where measurements were later carried out. Depth profiles of resistivity, mobility, and carrier concentration were measured by DHEM using an ALPro™ 50 electrical property profiling tool.

Figure 1 shows the cross-sectional TEM images of the P ion implanted samples after annealing at (a) 750°C, (b) 850°C, and (c) 950°C. As can be seen in Figure 1(a) the end of range (EOR) defects are located at approximately 26-30 nm from the surface in this sample. The 750°C RTA process did not adequately cure these defects. However, it is clear from the TEMs that defects at the original location of the a-Si/c-Si interface gradually shifted down when the samples were annealed at increasing RTA temperatures (see Figure 1(b–c)), when crystallinity of the ion implanted top layer also improved.

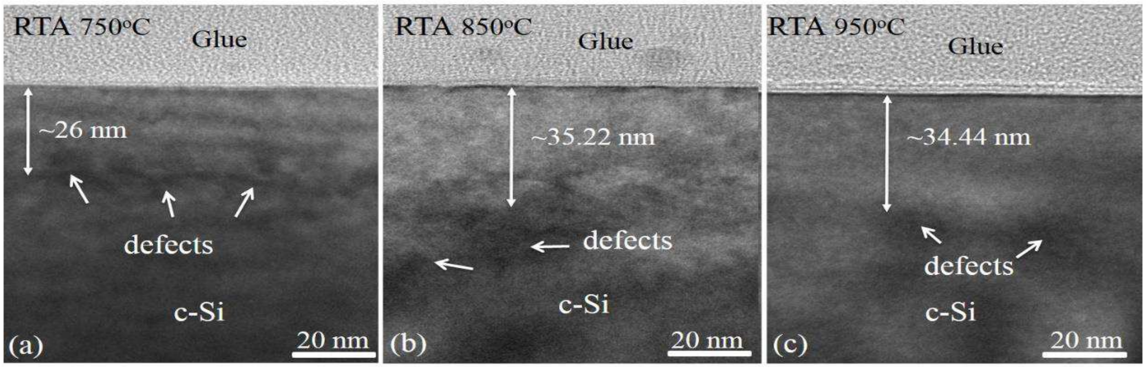

Figure 1. Cross sectional TEMs of three ion implanted samples after RTA at (a) 750°C, (b) 850°C, and 950°C.

The depth profiles of active carrier concentration obtained after RTA processes are given in Figure 2(a). Three regions can be discussed in these depth profiles. Region 1 is within 15-25nm of the surface, region 2 is at around 20-30 nm depth, and region 3 is at depths at or larger than about 35nm. As can be seen in this figure, increasing the RTA temperature results in diffusion of P impurities towards the Si substrate, and the active doping concentration at region 3 gets higher as the anneal temperature is increased from 750°C to 950°C. As for the region 1, we observe a small decrease in carrier concentration values with higher temperature (from about 3.8E+20 #/cm^3 to about 3.0E+20 #/cm^3) as the overall active dopant profile becomes more uniform due to diffusion.

Figure 2(b) shows the mobility depth profiles of the three samples discussed with reference to Figure 1 and Figure 2(a). It is obvious from this figure that the mobility profile is relatively flat within the implantation region (<30nm). Notably the mobility value for the RTA 750°C sample dips at a depth in the range of 25-30 nm, where Figure 1(a) shows extensive EOR defectivity. Therefore, the correlation with deteriorated mobility at that region is excellent. It is also clear from the mobility data that as the annealing temperature is raised to 850°C and then to 950°C, this dip in mobility disappears, and the mobility increases in the 30-35nm deep section suggesting reduction of defects through higher temperature annealing. In the deeper region (>35nm) mobility gets reduced with increasing annealing temperature because of increased carrier scattering mechanisms as more of the dopant is activated deeper at the elevated temperatures.

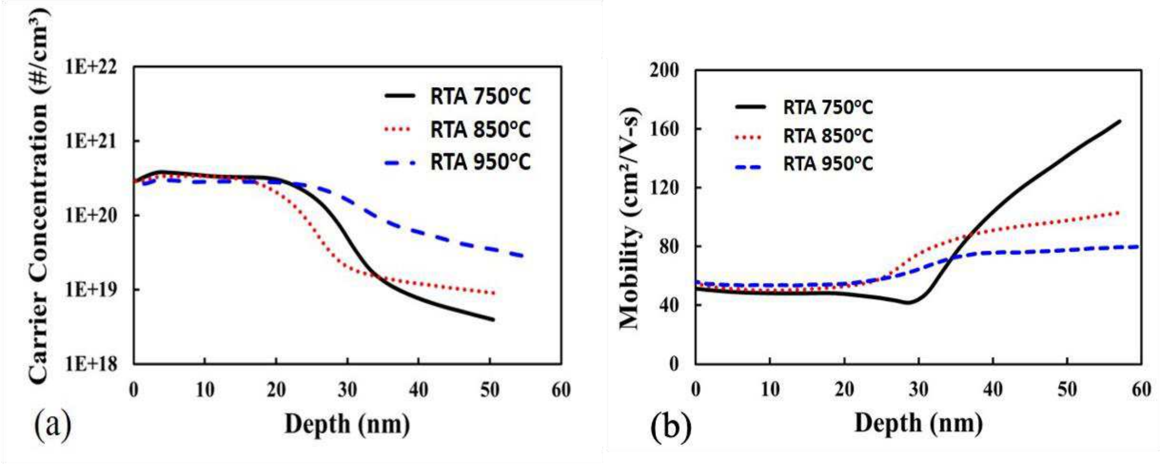

Figure 2. Depth profiles of (a) active dopants, and (b) mobility, measured by Differential Hall Effect Metrology (DHEM) technique for the samples of Figure 1.

Silicon-Germanium Alloy Layers

The boron doped Si$_{0.50}$Ge$_{0.50}$ epi-layer analyzed in this work was grown on a n-type 300 mm Si(001) wafer in an ASM Intrepid™ RP-CVD cluster tool. Before layer deposition, the wafer surface was cleaned by a conventional wet-chemical treatment. The native oxide was then removed in-situ using a pre epi bake in H$_2$ at a sufficiently high temperature (>1000°C), the within-wafer temperature uniformity profile being carefully optimized to avoid the formation of slip lines during this step. The layer was grown using SiH$_2$Cl$_2$, GeH$_4$ as Si and Ge precursors. B$_2$H$_6$ was used for p-type doping. HCl was added to the growth chemistry to achieve fully selective growth, further confirmed on Si oxide and nitride surfaces.

Figure 3 compares the B chemical concentration ([B]$_{chem}$) and layer resistivity (ρ) depth profiles extracted by SIMS and DHEM, respectively. The material resistivity is not constant throughout the layer. The lowest ρ values (< 0.5 mΩ.cm) are indeed observed close to the SiGe:B / Si interface. Then, ρ is found to increase with epi material thickness. Variations in resistivity correlate with variations in [B]$_{chem}$. A B spike is first observed at the SiGe:B / Si interface. Then, the B concentration profile exhibits a plateau at $[B]_{chem}$ ~ 3E+20 #/cm^3 before a gradual decay sets as the free surface is approached. As already reported in (3), B incorporation decreases as strain-relaxation occurs. Results presented in this contribution demonstrate an excellent correlation between this phenomenon and changes in SiGe:B electrical properties. We therefore believe that DHEM capabilities are of prime importance for the characterization and engineering of advanced contacts, for which local variations at the metal/semiconductor interface and its very close vicinity play a major role.

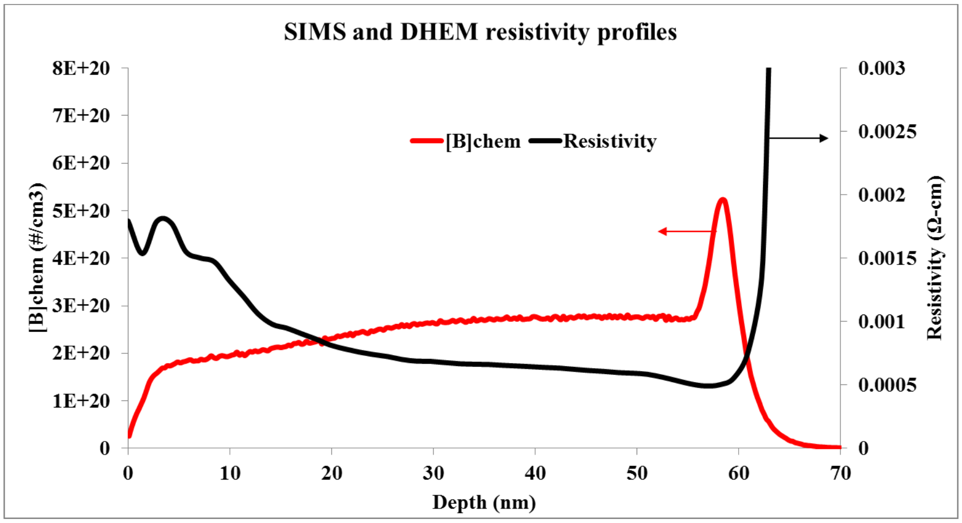

Figure 3. SIMS dopant depth profile and DHEM resistivity depth profile obtained from the B-doped SiGe(50%) epi layer characterized in this work.

References

1. A. Joshi and B. Basol, *Frontiers of Characterization and Metrology for Nanoelectronics Conference (FCMN)*, p.170 (2017).
2. P. Ramesh, K. Saraswat, A. Joshi, B. Basol, L. Wang and T. Buyuklimanli, *ECS Trans.*, 97(3), 75 (2020).
3. G. Rengo, C. Porret, A. Y. Hikavyy, E. Rosseel, N. Nakazaki, G. Pourtois, A. Vantomme and R. Loo, *ECS Trans.*, 98(5), 27 (2020).