B-2-2

Extended Abstracts of the 2013 International Conference on Solid State Devices and Materials, Fukuoka, 2013, pp598-599

Low NiGe Contact Resistances by Carrier Activation Enhancement (CAE) Techniques for Ge CMOSFETs

Hidenori Miyoshi[1], Tetsuji Ueno[1], Yoshihiro Hirota[1], Junji Yamanaka[2], Keisuke Arimoto[2], Kiyokazu Nakagawa[2] and Takanobu Kaitsuka[1]

[1]Tokyo Electron Ltd., 650, Mitsuzawa, Hosaka-cho, Nirasaki City, Yamanashi 407-0192, Japan
Phone: +81-551-23-4063, Email: hidenori.miyoshi@tel.com
[2]University of Yamanashi, 7-32 Miyamae-cho, Kofu, Yamanashi 400-8511, Japan

Abstract

Low NiGe specific contact resistivities (ρ_c) of 6.4×10^{-7} Ωcm^2 and 4.0×10^{-8} Ωcm^2 were obtained for n-Ge and p-Ge, respectively, by applying carrier activation enhancement (CAE) techniques. Theoretical calculation shows that, to achieve a ρ_c of 1×10^{-8} Ωcm^2 for ITRS 2015, PMOS only needs contact process optimization, while NMOS needs further CAE improvement and/or Schottky barrier height (SBH) reduction.

1. Introduction

Ge is an attractive candidate for new channel material due to its high electron and hole mobilities. However, further ρ_c reduction of metal/Ge contacts is still needed for high performance Ge CMOSFETs. The issue of strong Fermi level pinning near Ge valence band edge, which induces high ρ_c for NMOS, has not been solved yet [1-3]. On the other hand, CAE is the other key factor reducing ρ_c [4-8]. Kim *et al.*, reported that P/Sb co-implant enhances the dopant activation in Ge by reducing implant damage [4]. We previously showed that Ge pre-amorphization implant (PAI) enhances B activation in Ge by promoting amorphization before annealing [8].

In this work, we achieved low NiGe contact resistances both for n^+-Ge and p^+-Ge by the CAE techniques (P/Sb co-implant and Ge-PAI/B), which are based on a concept to acquire low ρ_c in Fig. 1. Experimental ρ_c values are discussed with theoretical ones. The guidelines for further ρ_c reduction are also described both for n^+- and p^+-Ge.

2. Experimental

Figure 2 shows a process flow for obtaining low NiGe ρ_c samples and Fig. 3 shows our ρ_c evaluation procedure using circular transfer length method (CTLM) [9]. We measured the resistance of each sample twice by changing probing positions because an entire region of one metal electrode is not equipotential for ρ_c of <~10^{-7} Ωcm^2. Theoretical ρ_c values were calculated by thermionic-field-emission and field-emission models [10] with SBH, carrier concentration, and material properties of germanium [11].

3. SBH and CAE Evaluation

The SBH of NiGe/n-Ge is found to be 0.60 eV in Fig. 4. The SBH of NiGe/p-Ge is estimated to be 0.07 eV because Ge band gap is 0.67 eV. We obtained very high carrier concentrations by the CAE techniques both for n^+- and p^+-Ge in Fig. 5. P/Sb co-implant enhances the carrier activation to 8.6×10^{19} cm^{-3} from 3.0×10^{19} cm^{-3} by single P implant (Fig. 5(a)). Ge-PAI/B also enhances the carrier activation to a world record of 8.4×10^{20} cm^{-3} (Fig. 5(b)), which was updated from the value we previously reported [8].

4. NiGe/n^+-Ge Contact

We investigated ρ_c dependence on Ni film thickness and activation annealing condition (Fig. 6), which alter the carrier concentration at NiGe/n^+-Ge interface, using the P/Sb co-implant profile in Fig. 5(a). The ρ_c values did not depend on the probing positions in CTLM in Fig. 3. The lowest ρ_c value was obtained with 50-nm Ni and activation at 500 ºC for 10 sec.

The obtained ρ_c value is 6.4×10^{-7} Ωcm^2 with an interface dopant concentration of 5×10^{19} cm^{-3} (Fig. 7). The ρ_c excellently coincides with the theoretical one. On the other hand, the ρ_c by single P implant in Fig. 5(a) is estimated to be 3×10^{-6} Ωcm^2. The CAE technique is considered to have reduced ρ_c by 80%. Our theoretical calculation shows that further improvement of high carrier concentration to 3×10^{20} cm^{-3} or reduction of SBH to 0.2 eV is required to achieve the ρ_c of 1×10^{-8} Ωcm^2 (ITRS 2015 [12]) for NMOS.

5. NiGe/p^+-Ge Contact

Using the Ge-PAI technique in Fig. 5(b), a very low ρ_c of 4.0×10^{-8} Ωcm^2 was obtained with a 2-D DC simulation including metal sheet resistance after measuring the two probing positions in CTLM in Fig. 3 (Fig. 9). The ρ_c of 4.0×10^{-8} Ωcm^2 is almost equal to the best value ever reported for p-Ge (2.7×10^{-8} Ωcm^2) [2]. When we see a boron concentration of 7×10^{20} cm^{-3} at the NiGe/p^+-Ge interface (Fig. 10), our calculation predicts a much low ρ_c of 1×10^{-9} Ωcm^2 based on the interface B density above (Fig. 11).

The wide ρ_c gap between experimental and theoretical ones is probably attributed to our non-optimized process. Figure 12 shows a result of TEM/EDX analysis on the NiGe/p^+-Ge sample and we found an oxide layer between Al and Ti films, which is probably due to oxidation in the air after Ti deposition. This kind of process issue can degrade contact resistance. Therefore, contact process optimization will lead to the satisfaction of the ρ_c requirement for ITRS 2015 and further ρ_c reduction to the theoretical value of 1×10^{-9} Ωcm^2 for PMOS.

6. Conclusions

Low NiGe ρ_c of 6.4×10^{-7} Ωcm^2 and 4.0×10^{-8} Ωcm^2 were obtained for n-Ge and p-Ge, respectively, by applying the CAE techniques (P/Sb co-implant and Ge-PAI/B). The CAE technique for n^+-Ge is considered to have reduced ρ_c by 80%. The obtained ρ_c for NiGe/p^+-Ge is almost equal to the best value ever reported for p-Ge. Theoretical calculation shows the guidelines for further ρ_c reduction. To achieve the ρ_c of 1×10^{-8} Ωcm^2 for ITRS 2015, PMOS only needs contact process optimization, while NMOS needs further CAE improvement and/or SBH reduction.

References

[1] T. Nishimura *et al.*, APL **91** (2007) 123123. [2] J. Oh *et al.*, SSDM (2010) P-3-20. [3] P. P. Manik *et al.*, APL **101** (2012) 182105. [4] J. Kim *et al.*, ESL **13** (2010) H12. [5] G. Thareja *et al.*, IEDM (2010) 10.5. [6] A. Firrincieli *et al.*, APL **99** (2011) 242104. [7] B. Yang *et al.*, ISTDM (2012) 9.5. [8] T. Ueno *et al.*, SSDM (2012) PS-1-8. [9] D. Schroder, *Semiconductor Material and Device Characterization 3rd ed.* (2006) 144. [10] K. K. NG *et al.*, TED **37** (1990) 1535. [11] L. Hutin *et al.*, ECS **156** (2009) H522. [12] ITRS 2011, Table FEP12.

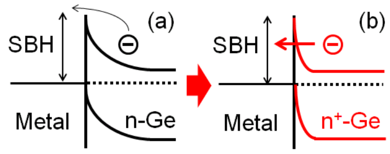


Fig. 1 Illustration of a concept in this work to acquire low ρ_c by the CAE techniques. Band diagrams for metal/n-Ge contacts are shown, for example, indicating (a) high ρ_c with low carrier concentration and (b) low ρ_c with high carrier concentration due to a thin thickness of a tunneling region.

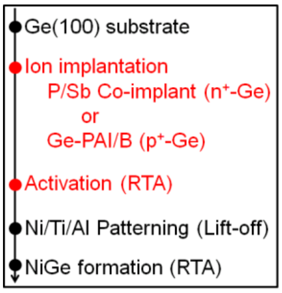
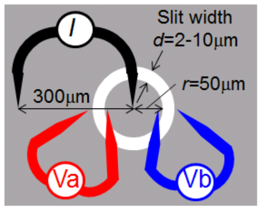


Fig. 2 A process flow with just one mask step for obtaining low ρ_c samples.



$$\frac{V}{I} = \frac{R_{sh}}{2\pi r}(d + 2L_T)C$$

Fig. 3 Schematic of CTLM for evaluating ρ_c. The resistance of each contact sample was measured twice with changing probing positions.

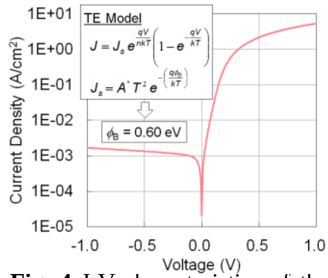


Fig. 4 J-V characteristics of the NiGe/n-Ge without implant. Based on thermionic emission (TE) model with ideality factor (n), the SBH (ϕ_B) of NiGe/n-Ge is found to be 0.60 eV.

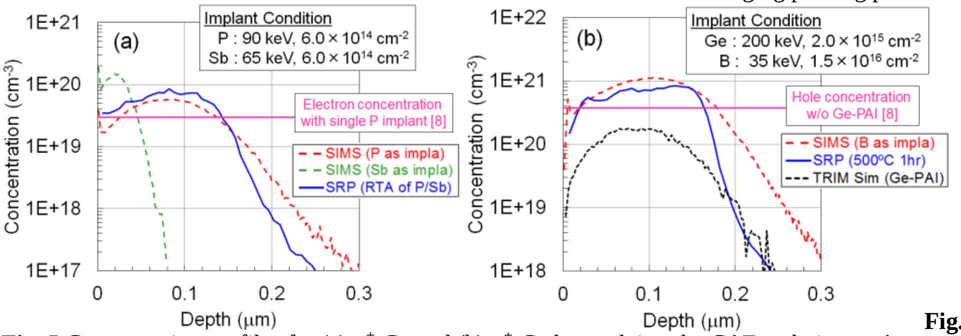


Fig. 5 Concentration profiles for (a) n⁺-Ge and (b) p⁺-Ge by applying the CAE techniques. A maximum electron concentration of 8.6×10^{19} cm^{-3} and a world record hole concentration of 8.4×10^{20} cm^{-3} have been confirmed. These values are higher than those for single P implant and B implant without Ge-PAI, respectively.

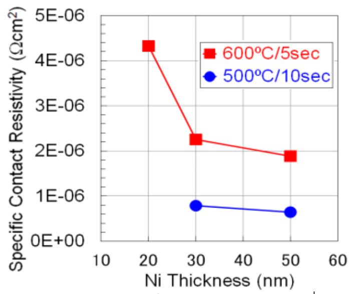


Fig. 6 ρ_c values for the NiGe/n⁺-Ge contact samples. The P/Sb co-implant condition was the same as Fig. 5(a). The lowest ρ_c value was 6.4×10^{-7} Ωcm^2.

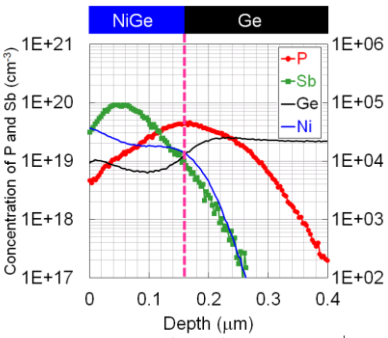


Fig. 7 SIMS profile of the NiGe/n⁺-Ge contact sample for the ρ_c of 6.4×10^{-7} Ωcm^2. The dopant concentration at the NiGe/n⁺-Ge interface is 5×10^{19} cm^{-3}. Ge and Ni signals are used to determine the NiGe/n⁺-Ge interface.

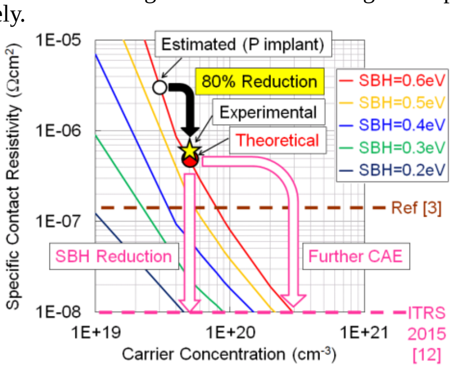


Fig. 8 Theoretical calculation of ρ_c on n-Ge(100) showing excellent consistency with the experimental ρ_c. The CAE technique is considered to have reduced ρ_c by 80%. The obtained ρ_c using NiGe is slightly higher than the best value ever reported for n-Ge using different contact materials with the lower SBH [3]. To achieve the ρ_c for ITRS 2015 for NMOS, further CAE improvement and/or SBH reduction is required.

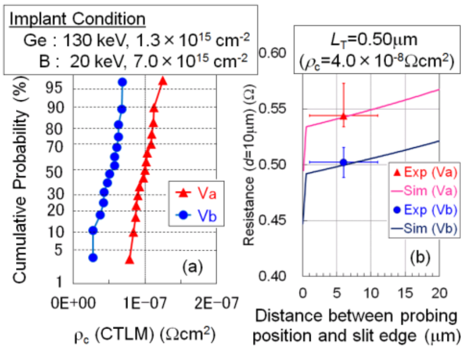


Fig. 9 (a) ρ_c values measured by CTLM depend on the position of voltmeters. (b) 2-D DC simulation results by changing L_T as a fitting parameter. The extracted ρ_c was 4.0×10^{-8} Ωcm^2. Activation was performed at 540 ºC for 10 sec. Ni thickness was 20 nm.

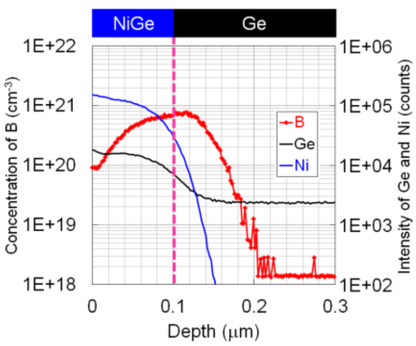


Fig. 10 SIMS profile of the NiGe/p⁺-Ge contact sample for the ρ_c of 4.0×10^{-8} Ωcm^2. The boron concentration at the NiGe/p⁺-Ge interface is 7×10^{20} cm^{-3}.

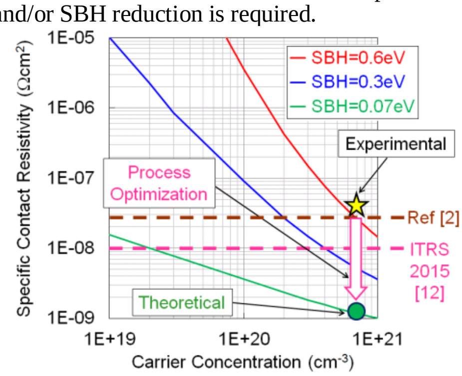


Fig. 11 Theoretical calculation of ρ_c on p-Ge(100) and the experimentally obtained ρ_c. The process optimization will achieve the theoretical ρ_c of 1×10^{-9} Ωcm^2 for PMOS.

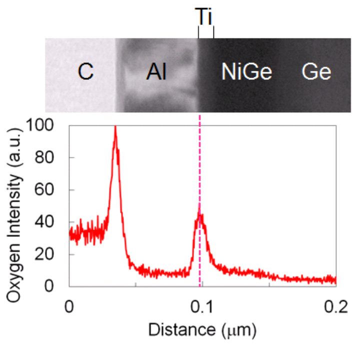


Fig. 12 TEM image and the oxygen intensity (EDX) of the NiGe/p⁺-Ge contact sample. An oxide layer between Al and Ti films was confirmed. We think this oxide layer induces the higher ρ_c value than the theoretical one.