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CMOS Contact Resistance Reduction through Aluminum Profile Engineering

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Abstract

External series resistance (R_{EXT}) has been identified as one of the key challenges for achieving continual improvement of speed performance in the scaling of field-effect transistor (FET) technology. Contact resistance (R_{CON}) between the metallic contact and the source/drain (S/D) region is a major contributor to the R_{EXT}, and needs to be minimized. Technology options for reducing R_{CON} with aluminum (Al) profile engineering across the metallic contact/Si interface will be reviewed.

Introduction

Channel strain engineering has been a workhorse in IC manufacturing to increase the carrier mobility and transistor drive current. With the aggressive scaling of gate length, the channel resistance is reduced significantly due to shorter distance between the source and drain and higher strain effect from the S/D stressors. As such, R_{EXT} has become an increasingly critical component which could limit transistor performance enhancement brought by strain engineering [1].

R_{CON} between the metallic contact and the S/D region [see Fig. 1] contributes to a major portion of R_{EXT}, and needs to be reduced [1]. R_{CON} is an exponential function of the Schottky barrier height (SBH). To alleviate the escalating R_{EXT} issue in advanced Si transistors, innovative solutions for SBH lowering have been explored [Fig. 2]. These approaches can be broadly classified into the following: (1) workfunction tuning with near band-edge metallic contact and (2) effective SBH reduction with interface engineering.

Aluminum (Al) has been shown to be effective for SBH tuning for both n^+ and p^+ S/D [2]-[7]. Forming Ni(Al)Si alloy contact can lead to R_{CON} reduction on n^+ S/D [2]. Implanting and segregating Al at NiSi/Si interface results in R_{CON} lowering on p^+ S/D [7]. In this paper, we discuss two distinct technology techniques to engineer the Al profile in Ni-based silicides contacts for Φ_B tuning.

SBH Tuning with Al Implant and Pulsed Laser Anneal

Laser annealing (LA) has been demonstrated as a possible alternative to conventional rapid thermal annealing for silicide formation [8]. Low thermal budget associated with LA suppresses nickel diffusion and hence minimize silicide piping issues [8]. Given that LA can be a potential option for silicide formation, the effect of pulsed laser anneal (PLA) on SBH modulation of silicides with Al incorporation was investigated [5].

To investigate the impact of PLA on forming silicides with Al incorporation, Schottky contacts devices were fabricated on p-Si. Shallow Al implant was introduced into the samples prior to nickel (Ni) deposition and silicidation [Fig. 3]. Fig. 4 shows the TEM images of silicide films formed at different annealing conditions. The TEM images reveal that atomically flat silicide/Si interface is achieved for films formed using PLA [Fig. 4(b)-(c)] as compared to a much rougher interface for sample formed using conventional RTA [Fig. 4(a)]. By increasing the laser fluence, the nickel silicidation covers a greater depth and a thicker NiSi is formed.

Fig. 5(a) shows the *I-V* characteristics of contacts formed at different laser fluences. *I-V* curve of sample with no Al implant and silicided using conventional RTA is included as a reference. The effective hole SBH (Φ_B^P) for the experimental splits were extracted and summarized in Fig. 5(b). A near ohmic contact was observed for samples annealed at high laser fluences (i.e. 500 mJ/cm^2 and 700 mJ/cm^2). This indicates a low Φ_B^P is achieved. In contrast, the contacts show rectifying characteristics (i.e. high Φ_B^P) when formed at low laser fluences (i.e. 200 mJ/cm^2 or 300 mJ/cm^2).

SIMS profiles [Fig. 6] show that the degree of SBH modulation is strongly dependent on the Al distribution in the silicide. SIMS analysis reveals Al segregation near the silicide/Si interface for sample annealed at laser fluence of 700 mJ/cm^2 (high fluence). For sample irradiated at 200 mJ/cm^2 (low fluence), the SIMS analysis shows a high concentration of Al within the silicide. It is believed that, high laser fluence ionized the Al atoms snowplowed at the silicide/Si interface, and reduced the tunneling barrier width. Narrow barrier width increases the hole tunneling probability and contributes to the Φ_B^P reduction. Simulations predict that the maximum temperature generated in the samples irradiated at 700 mJ/cm^2 and 200 mJ/cm^2 could be as high as ~1820 K and ~890 K, respectively. The low instantaneous temperature during laser irradiation at low fluence may result in lesser Al activation at the silicide/Si interface as compared to those annealed at high fluences. Incorporation of high concentration of Al within the silicide is believed to have resulted in a reduction of the intrinsic workfunction of the silicide, leading to an increase in Φ_B^P.

Al Profile Engineering with Carbon for SBH Modulation

Another way to engineer the Al profile within the silicide can be achieved with carbon (C) incorporation [6]. *I-V* characterization reveals an increase in reverse current for NiSi/*p*-Si contact with Al implant only, suggesting a reduction in the effective Φ_B^P. This is consistent with Ref. [7]. In the presence of C implant, a 10^4-fold reduction in reverse current for the *I-V* plot of NiSi/*p*-Si contact with Al implant indicates an increment (or a reduction) in the effective Φ_B^P (electron SBH Φ_B^N).

The reason for the different SBH outcome is related to the Al distribution in the silicide [Fig. 8]. In the absence of C implant, Al segregation at the NiSi/Si interface is observed, leading to an increase (reduction) in the effective Φ_B^N (Φ_B^P). Al concentration at the NiSi/Si interface reduces drastically in the presence of C implant, suggesting that bulk of Al remains in NiSi. This correlates to a reduction (increase) in the effective Φ_B^N (Φ_B^P). The C SIMS profile reveals a homogenous distribution of C within the NiSi [Fig. 9]. It is believed that the presence of C along the NiSi grain boundaries probably hinders the diffusion of Al towards the NiSi/Si interface.

The novel silicidation process was integrated in strained nFETs with Si:C S/D stressors using the process flow in Fig. 10 to verify the feasibility of this new Φ_B^N reduction technology. Cross-sectional TEM images [Fig. 11] of the S/D region of a final device with Ge PAI and Al implant after NiSi formation, reveals complete consumption of amorphized region created by the Ge and Al implants. At an I_{Off} of 300 nA/μm, I_{On} for nFETs with Al implant is ~18% higher than that of control (no Al implant) [Fig. 12]. Comparison of the R_{EXT} of nFETs with and without Al implant [Fig.13] shows that mean R_{EXT} decreases by ~53% from ~1230 Ω·μm for control devices to ~580 Ω·μm for nFETs with Al implant. This is due to reduced $\Delta\Phi_B^N$ at the NiSi:C/Si:C interface. Fig. 14 shows comparable subthreshold swing SS at different DIBL indicating that the I_{Off} are not compromised with Al implant.

Conclusions

Two distinct Al profile engineering techniques for achieving either Φ_B^N or Φ_B^P reduction were discussed. These technologies, coupled with reported R_{CON} reduction for pFET with Al [7], opens up new avenue to realize a novel single metal silicide integration solution with dual band edge barrier heights for selective R_{CON} optimization in CMOS technology.

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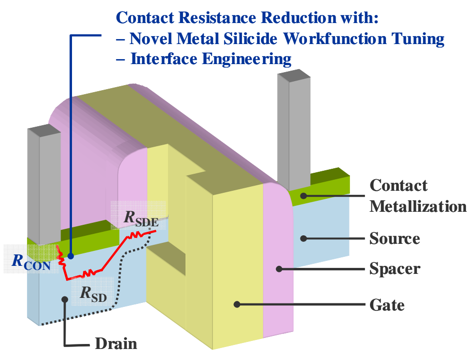


Fig. 1. In aggressively scaled devices, high R_{EXT} would compromise drive current. R_{CON} is a major component of the R_{EXT}.

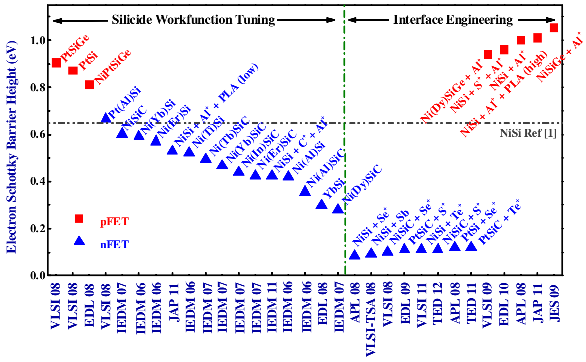


Fig. 2. Electron SBH of various metallic contacts on Si, SiGe or Si:C substrate. SBH tuning can be achieved with contacts with near band-edge workfunction or silicide/Si interface engineering.

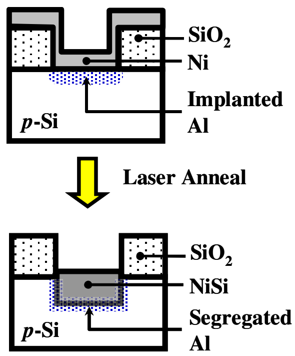


Fig. 3. Schematics showing the process flow of forming Al-implanted contacts with pulsed laser anneal (PLA).

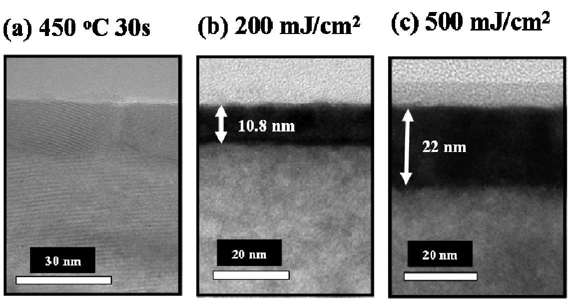


Fig. 4. TEM images of silicide films formed with (a) conventional RTA at 450 °C for 30 s or after PLA of (b) 200 mJ/cm^2 and (c) 500 mJ/cm^2.

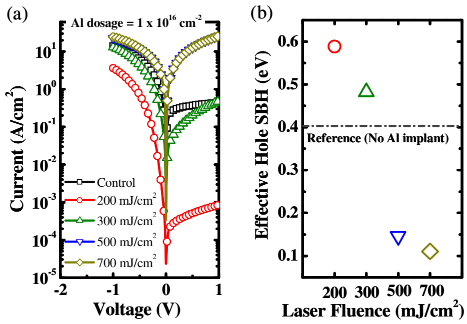


Fig. 5. (a) *I-V* characteristics of contacts formed at various PLA fluences. (b) Comparison of the average Φ_B^P as a function of PLA fluences.

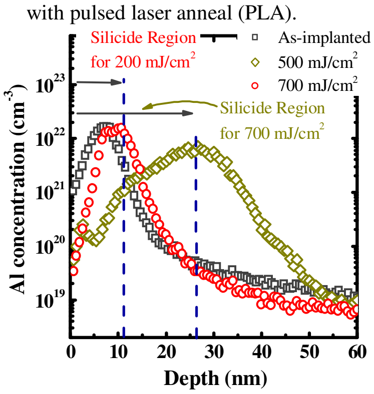
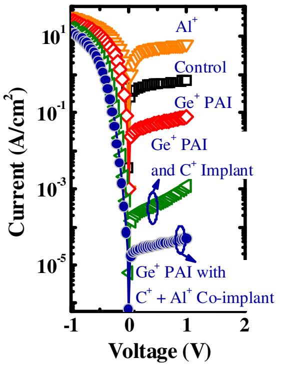
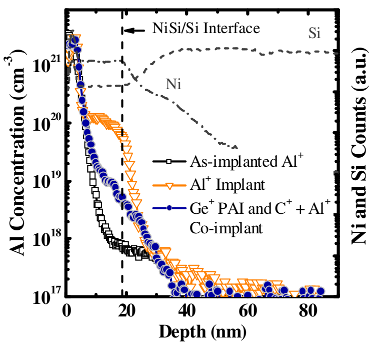
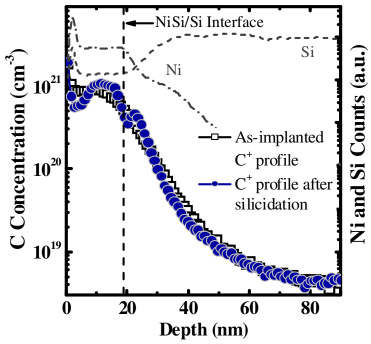


Fig. 6. SIMS profiles of Al after Ni deposition and silicidation at laser fluences of 200 mJ/cm^2 and 700 mJ/cm^2.







Process Flow

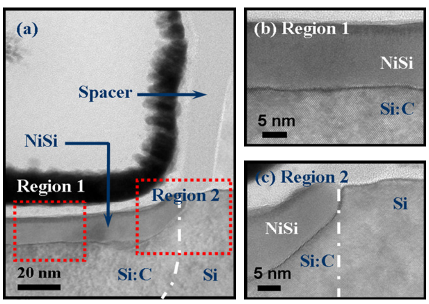
- Gate Stack and Spacer Formation
- C^+ and Deep S/D Implants
- Si:C S/D Stressors Formation and S/D Activation Anneal
- S/D Implant Splits:
  a) Control
  b) Ge^+ PAI + Al^+ implant
- Ni Metal Deposition
- Silicidation at 450°C 30 s

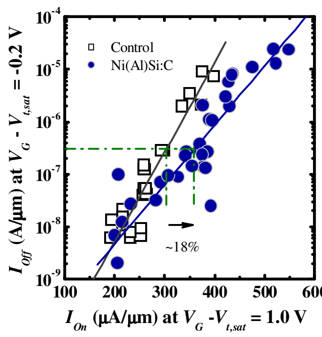
Fig. 7. *I-V* characteristics of Al-implanted contacts formed with and without C implant.

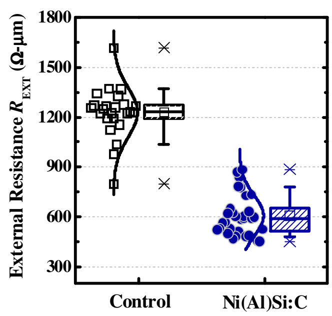
Fig. 8. SIMS analysis reveals Al segregation at the NiSi/Si interface for sample without C incorporation.

Fig. 9. SIMS analysis shows C segregation at the NiSi/Si interface and homogenous C distribution within the NiSi.

Fig. 10. Key process steps for R_{CON} reduction with Al implantation for strained n-FETs with Si:C S/D stressors.







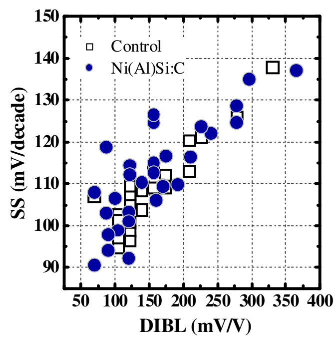


Fig. 11. (a) TEM image of the silicided SD region of nFET with Si:C S/D stressors. (b)-(c) High-resolution TEM images reveal uniform NiSi:C formed on Al implanted S/D regions.

Fig. 12. At I_{Off} = 300 nA/μm, Si:C S/D nFETs with Al implant has 18% higher I_{On} than Si:C S/D nFETs without Al implant.

Fig. 13. Mean R_{EXT} reduces by ~53 % with Al implant. The reduction in R_{EXT} is attributed to the lowering of the Φ_B^N at the NiSi:C/Si:C interface.

Fig. 14. Matching SS at fixed DIBL suggests Al incorporation has negligible impact on I_{off}.