Extended Abstracts of the 2008 International Conference on Solid State Devices and Materials, Tsukuba, 2008, pp. 686-687

A-6-1

Self-limiting Growth Behavior of Epitaxial $NiSi_2$ and its Impact on Controlled Silicidation of Metal Source/Drain in Silicon Nanowire MOSFETs

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1. Introduction

Metal source/drain (S/D) is indispensable for upcoming aggressively scaled metal-oxide-semiconductor field effect transistors (MOSFETs) [1-4]. It contributes to reduction of parasitic resistance without the need for abrupt junction profile.

When metal S/D is applied to silicon nanowire (SNW) MOSFETs, however, narrow width effect in silicidation [5] will emerge as a major issue as illustrated in **Fig. 1**. Because of the difficulty of controlling the silicidation reaction in a small-body silicon, silicide phase becomes disordered and excess silicidation invades the channel region.

In this report, we present a unique growth behavior of epitaxial $NiSi_2$ film and discuss its potential of controlling the silicidation process in small body silicon.

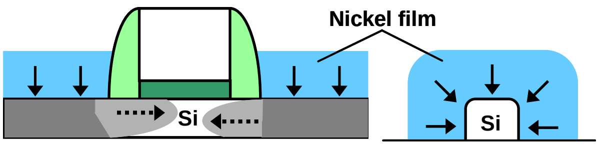

Fig. 1 Schematics showing silicidation issues of metal source/drain in SNW MOSFETs. Because of the narrow width effect, silicide phase becomes disordered and junction position will be uncontrollable.

2. Experimental

Nickel films were deposited by sputtering in two typical conditions; one in Ar gas and another in Ar/N_2 mixture gas. The latter condition forms nitrogen (N)-doped Ni film, which was confirmed by physical analyses. Experimental flow is shown in **Fig. 2**. Si(100) substrates were mostly used, and poly-Si films on SiO_2 layer and SNW were used for some experiments.

Crystalline phases of silicides were determined by in-plane X-ray diffraction (IPXRD). The amount of metal atoms in the films was analyzed by X-ray fluorescence (XRF). Combining the XRF data with IPXRD results, thicknesses of silicide films were evaluated. Grazing incident X-ray reflectivity (GIXR), on the other hand, was used to analyze the thickness, density, and interfacial roughness of epitaxial $NiSi_2$ films accurately.

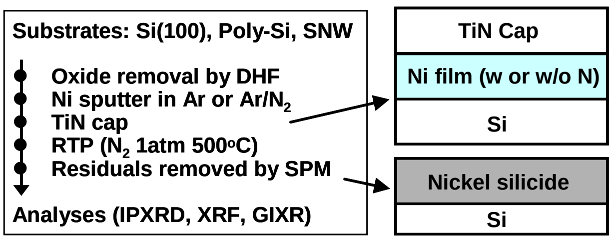

Fig. 2 Experimental flow of nickel silicides formation.

3. Results and Discussion

N-doping in Ni films is effective to formation of $NiSi_2$ crystalline phase by 500°C annealing. Comparative silicidation studies using Ni and N-doped Ni films are shown in **Fig. 3**. Poly-crystalline and epitaxial $NiSi_2$ films are obtained by depositing N-doped Ni films followed by annealing at 500°C, although the applied annealing temperature 500°C is the typical condition for NiSi phase formation and annealing temperature higher than 800°C is generally required for $NiSi_2$ formation. Epitaxial growth of $CoSi_2$ and $NiSi_2$ films by low temperature annealing is also attainable by inserting thin oxide layer [6] and depositing Ti/Ni bi-layer structure [7]. According to these results, it is concluded that the key factor in obtaining epitaxial disilicides is the control of metal atom diffusion rate into Si. The effect of the N-doping technique in this study is also considered as forming a SiN barrier layer on Si surface or preventing the fast diffusion of Ni atom by creating a weak Ni-N bonding.

A unique growth behavior is found in the epitaxial growth of $NiSi_2$ films. Dependence of silicide film thick-

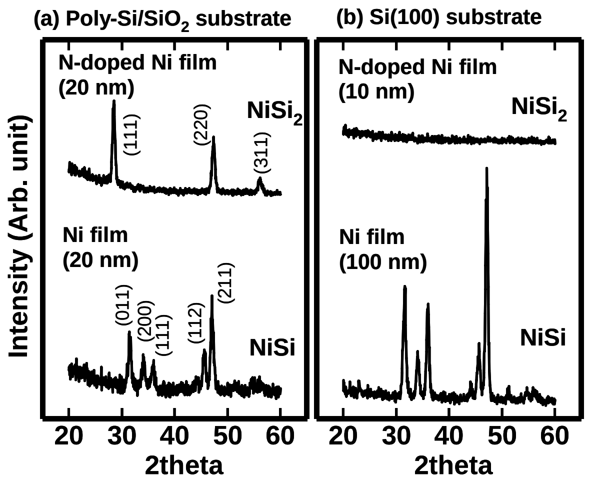

Fig. 3 In-plane XRD patterns of nickel silicides prepared by annealing at 500°C for 60 s on poly-Si (25 nm)/SiO_2 and Si(100) substrates. (a) Poly-crystalline NiSi film is obtained by 20 nm-thick Ni film on poly-Si. On the other hand, poly-crystalline $NiSi_2$ film is obtained by 20 nm-thick N-doped Ni film. (b) Poly-crystalline NiSi is obtained by 100 nm-thick Ni film on Si(100) substrate. Disappearance of diffraction peaks in the case of 10 nm-thick N-doped Ni film indicates the epitaxial growth of $NiSi_2$ film on Si(100).

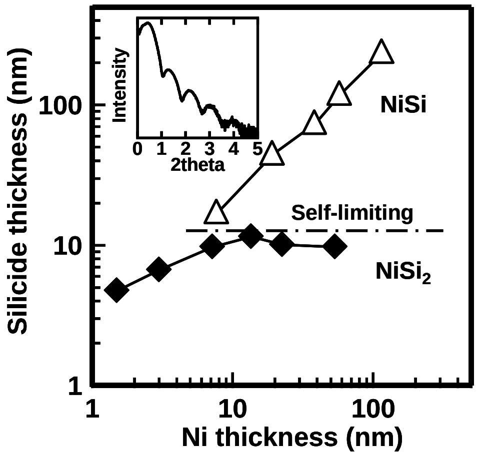

Fig. 4 The relationships between the silicide thickness and the deposited Ni thickness for NiSi and epitaxial $NiSi_2$ films on Si(100). All samples were annealed at 500°C for 60s. A self-limiting growth behavior is observed in epitaxial $NiSi_2$ films. The inset is a GIXR result of epitaxial $NiSi_2$ film, prepared by 22 nm-thick N-doped Ni film. The thickness, density, and interface roughness are analyzed to be 10.1 nm, 4.82 g/cm^3 (4.803 g/cm^3 in calculation), and 0.7 nm, respectively.

ness upon the deposited Ni film thickness is examined in detail and summarized in **Fig. 4**. NiSi films grow in proportion to the deposited Ni thickness, even in the case of 100 nm-thick Ni film. In contrast, it is surprising that the epitaxial $NiSi_2$ films exhibit a self-limiting growth behavior. The $NiSi_2$ thickness is saturating at around 10 nm even in the case of 50 nm-thick N-doped Ni film deposition.

We consider that the difference between the growths of NiSi and epitaxial $NiSi_2$ is brought about by two distinct diffusion behaviors of Ni atom, as shown in **Fig. 5**. The growth of poly-crystalline NiSi film is promoted by a fast diffusion of Ni atoms through the grain boundaries. Entire silicidation of 100 nm-thick Ni film into NiSi film by annealing at 500°C for 60s is understandable by this mechanism. In contrast, the growth of epitaxial $NiSi_2$ film proceeds by lattice diffusion of Ni atom, owing to the 0.4%-small lattice mismatch between $NiSi_2$ and Si. In a comparative study of diffusion coefficients of Ni atom between grain boundary diffusion and lattice diffusion in Ni_2Si crystal, it is reported that they differ as large as 5 orders [8]. Thus the growth rate of epitaxial $NiSi_2$ film is governed by the lattice diffusion and is very slow when compared with that of poly-crystalline NiSi film. The self-limiting growth manner observed in epitaxial $NiSi_2$ growth is an evidence that the growth thickness is controlled by the annealing temperature and time, not by the deposited Ni thickness.

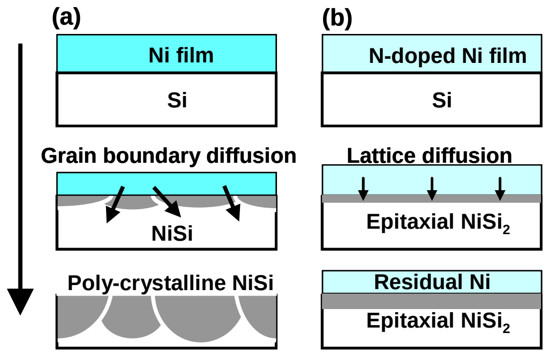

Fig. 5 Models explaining the different growth behavior of NiSi and epitaxial $NiSi_2$ films. (a) NiSi film growth is promoted by the fast diffusion of Ni atoms via grain boundaries. (b) Epitaxial $NiSi_2$ film growth starts by the assist of nitrogen in Ni film and progresses by lattice diffusion of Ni atom. Its growth rate is very slow and is useful for metal S/D silicidation in SNW MOSFETs.

The slow growth rate attained in epitaxial $NiSi_2$ has a great impact on fabrication of metal S/D in SNW MOSFETs. It is no more necessary to adjust the Ni deposition thickness precisely because the $NiSi_2$ single phase is naturally formed and its growth front is controllable by annealing temperature and time. Epitaxial $NiSi_2$ growth is also helpful to formation of atomic-scale flat junction [3].

Finally, epitaxial growth technique of $NiSi_2$ is actually applied to a SNW structure, as shown in **Fig. 6**. By the deposition of sufficient thickness of N-doped Ni film, the SNW structure is fully silicided without residual Si region. Judging from the clear and regular lattice image, the SNW is transformed into epitaxial $NiSi_2$ completely.

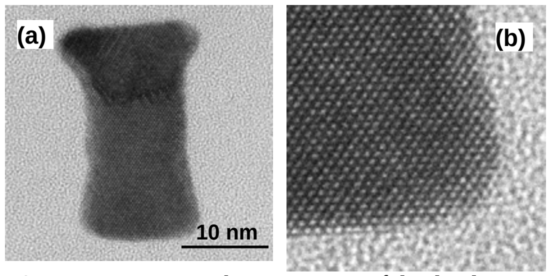

Fig. 6 XTEM images showing successful silicidation of a prototype SNW structure by depositing sufficient N-doped Ni film and annealing at 500°C for 60s. (a) A SNW with 10 nm width and 25 nm height is fully silicided. (b) A magnified image indicates the epitaxial growth of $NiSi_2$.

4. Conclusion

Self-limiting growth behavior observed in epitaxial $NiSi_2$ manifests that the film growth is driven by lattice diffusion mechanism and not by grain boundary diffusion. Formation of single $NiSi_2$ phase at a practically slow growth rate is a powerful tool for the silicidation of Metal S/D in SNW MOSFETs.

Acknowledgement

This work was partly supported by METI as part of the Innovation Research Project on Nanoelectronics Materials and Structures.

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