

Optical Properties of Bonded Silicon Silicide on Insulator (S²OI) -A New Substrate for Electronic and Optical Devices

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Abstract

A new type of Silicon on Insulator substrate was fabricated using wafer bonding. The inclusion of a highly conducting buried tungsten silicide layer below the silicon device layer but above the oxide film results in many attractive properties for electronic and optical devices such as high performance bipolar transistors, power devices and optoisolators. Commercial products are being developed using this new S201 material. However, to fully exploit this material a detailed understanding of its optical and physical nature is required. To this end a study of the buried silicide film, its interfaces and the overlying silicon was carried out using Spectroscopic Ellipsometry and Atomic Force Microscopy. It was found that the buried silicide undergoes a structural transformation, due to the thermal bonding anneal, resulting in a rough interface between it and the silicon overlayer .

Key Words: Wafer bonding; spectroscopic ellipsometry, atomic force microscopy, silicon materials, tungsten silicide

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1. Introduction

Silicon silicide on insulator (S^2OI) materials are formed by wafer bonding techniques [1]. Wafer bonding allows many new opportunities for the integration of dissimilar materials in novel structures and devices. S^2OI wafers are currently in production and being applied to commercial products using a thick top silicon layer around 20 μm . However, to apply this new material to many other electronic and optical devices thinner top silicon films ($<3\ \mu$) are necessary. To manufacture such wafers reliably it is necessary to be able to measure the top silicon film thickness accurately with conventional techniques such as spectroscopic ellipsometry and reflectometry. Indeed one of the techniques used to thin bonded silicon on insulator materials is a localised plasma assisted chemical etching (PACE) technique [2]. For this to be effective a map of top silicon thickness, generated by reflectometry, is required for the PACE tool. For such measurements to be carried out accurately, the optical properties of the buried silicide and the nature of its interfaces must be well understood for appropriate optical models to be used for thickness calculations.

In this paper we report new optical reference data for wafer bonded buried tungsten silicides in comparison to as-deposited (by chemical vapour deposition) tungsten silicide. This data can only be used to model S^2OI structures accurately only when the interfacial roughness between the top silicon/buried silicide and the crystallisation of the silicide, during thermal bonding, are taken into account. Interfacial roughness data was collected using atomic force microscopy (AFM) after removal of the top silicon by various means.

2. Experimental

Starting S^2OI materials were fabricated as described in reference [1] with a final top silicon layer thickness of around 3 μm , a buried silicide of around 0.3 μm and a buried oxide of around 1.2 μm . A SOPRA research ellipsometer (ES4G) was used to obtain SE data and a Digital Instruments 3000 AFM was used to measure surface structure and roughness.

2.1 Spectroscopic Ellipsometric Data

SE data were collected from the S² OI structures after a) selective chemical removal and alternatively b) conventional chemo-mechanical polishing of the Si to reveal the buried silicide. The two approaches resulted in widely differing optical behaviour for the exposed silicide films. Figure I shows the n and k values calculated from a direct inversion of the ellipsometric data for the as-deposited (prior to bonding), chemically etched and polished silicide (post-bonding) surfaces. Smoothly varying n and k spectra for the as-deposited film are converted to spectra showing structure near 300 nm and 350 nm (similar to crystalline silicon), for the bonded S²OI silicides. An additional peak is seen in the n at 500 nm where the k values drop significantly to about 1.5 while that of the as-deposited tungsten silicide remain high at about 2.5. The origin of the 500 nm transition is not clear at present but may be associated with a new transition from crystalline tungsten silicide [3] formed during the high temperature (> 1000°C) bonding anneal. Further work is required to clarify its origin.

2.2 AFM Roughness Analysis

The origin of the difference between the chemically etched and polished materials is due to interfacial roughness as-revealed by the chemical removal of the top silicon. The selectivity of the etching solution used is very high and the silicide remains intact as a continuous film. AFM measurements of the as-deposited, chemically etched and polished surfaces are shown in Figure 2. The RMS roughness of the as-deposited silicide is about 2 nm (RMS). This is increased to around 17 nm (RMS) for the etched surface, while the polished silicide is again around 2 nm (RMS). The AFM image of the etched sample shows clearly the granularity of the silicide film with grains displaying sharp facets. For the polished sample (where a process the silicide film with grains displaying sharp facets. For the polished sample (where a process typically used for bulk silicon was applied) some remnants of the granularity can be seen. There is also a fine scale roughness dominating at length scales less than 50 nm which is less evident in the etched sample and thus may have resulted from the polishing. Hence while the polishing may appear to be incomplete it did reduce the roughness significantly.

2.3 Spectroscopic Ellipsometry Modelling

AFM confirmed that the silicon/silicide interface was much rougher than the as-deposited silicide surface. The SE data collected from the rough surface was then modelled using the n and k values calculated from the smooth surface with an Effective Medium Approximation (EMA) roughness layer. The fitted layer thickness was 15.1 ± 0.7 nm, with a void fraction 0.32 ± 0.01 (shown in Figure 3) which is close to the AFM RMS value of 17.4 nm. Given the non-ideal polished silicide surface with an AFM RMS roughness of around 2 nm (and the possibility of surface oxide layers which were not accounted for) the results appear consistent even if the SE fit is not perfect.

To check the self consistency of the new SE reference data, a thin S^2OI sample was measured and fitted using a simple model of the polished silicide, an interfacial roughness layer and the top Silicon. The fit is shown in Figure 4. Again while the fit may not be perfect the interfacial roughness calculated (15.9 ± 0.6 nm) is similar to that arrived at above and the fraction of silicon (0.40 ± 0.07) in the interlayer matches the void fraction in the roughness layer for the etched sample. This clearly demonstrates that the S^2OI materials can be modelled using the new data once the interfacial roughness is taken into account. Indeed this thin layer S^2OI was produced by bonding a SIMOX wafer with an initial starting silicon layer of around 0.24 μm .

3. Discussion and Conclusion

The thermal anneal required for bonding causes the formation of large crystallites of tungsten silicide from the original near amorphous (or nanophase) deposited silicide layer. As a direct consequence a rough interface between the overlying silicon and silicide layer results. The process of grain growth is not clear and requires further detailed analysis. However, given the composition of the as-deposited silicide is typically $WS_{1.7}$ i.e., it is mostly silicon, the grain growth may follow a similar pattern to pure poly-crystalline silicon films where high temperature thermal anneals result in similar large grained structure by a mechanism of growth competition between nuclei of differing sizes. The consequences for the optical properties of the buried bonded silicide films are notable. The crystallised silicide appears to display the optical properties of silicon in the shorter wavelength range and the properties of tungsten in the longer wavelengths. This is even more notable in the infra-red, beyond 1.0um, which will be discussed elsewhere.

Allowing for the uncertainties of surface oxide films and a non-ideal level of surface roughness it is quite clear that the new data collected for the recrystallised silicide are adequate to determine overlying silicon film thickness and the interfacial roughness that exists between the two layers. The high k values throughout the spectrum mean that a simple model can be applied and any uncertainties with the materials below the silicide play no part. Modelling of a thick film S^{201} (around 3um Si top layer) was also successfully demonstrated and will be discussed elsewhere.

In conclusion a detailed analysis of the optical properties of buried tungsten silicide and its interfacial roughness was carried out using SE and AFM. The new data collected and the understanding gained will allow routine measurements of silicon top layer thickness in S²OI materials which form a new class of substrates directly applicable to a number of advanced optical and electronic devices.

Acknowledgements

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Figure Captions

1. Optical constants of as-deposited, wet etched and polished tungsten silicide layers.
2. AFM images of the surfaces of (a) as-deposited, (b) wet etched and (c) polished tungsten silicide layers. Note the different z-range for the etched sample.
3. (a) $\tan \delta$ (b) $\cos \delta$ fits for the etched silicide using the reference data from the polished silicide.
4. (a) $\tan \delta$ (b) $\cos \delta$ fits for a thin SiO_2 sample, yielding a structure consisting of 2 nm surface native oxide, 239.4:±1.7 nm of Si, 15.9 ±0.6 nm interfacial roughness layer (with a 0.4 ±0.07 fraction of Si mixed with silicide) and the underlying silicide.

















