Fabrication of SOI structure with AlN film as buried insulator by Ion-Cut process

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Abstract

Self-heating effects in silicon-on-insulator (SOI) devices limit the applicability of SOI materials in electronics in cases where high power dissipation is expected. Aluminum nitride (AlN) as a potential candidate for buried insulator materials in SOI structures has been investigated. Uniform AlN films were grown on 4 in. Si(1 0 0) wafers using ion-beam-enhanced deposition (IBED) under optimized experimental conditions. The films have excellent dielectric properties and a smooth surface with roughness rms values of 0.13 nm, and are good enough for direct bonding. SOI structure with the AlN film, as buried insulator, was successfully formed by the Ion-Cut process.

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1. Introduction

For many device applications, silicon-on-insulator (SOI) offers several advantages compared to bulk silicon substrates. SOI technology simplifies device processing due to easier device insulation. It also gives reduced parasitic capacitances resulting in increased speed and lower power consumption. Furthermore, increased radiation hardness is obtained. The two common techniques for the formation of SOI are separation by implanted oxygen (SIMOX)\textsuperscript{[1]} and Smart-Cut or Ion-Cut\textsuperscript{[2]}. In principle, the SIMOX technique is limited to buried layers of silicon dioxide or nitride while the Ion-Cut process allows more flexible combinations of different materials. The latter process is thus the technique to fabricate complex SOI structure with buried layers other than silicon dioxide.

In most SOI structures using SiO\textsubscript{2} as the buried layer limits its applications in high temperature, high power integrated circuits because of its lower thermal conductivity. Replacement of the buried silicon dioxide by a better thermal conductor may lead to improved performance and permit increased power dissipation. One of the interesting candidates for such a buried insulator is aluminum nitride (AlN)\textsuperscript{[3]}, which has been investigated due to attractive properties
including excellent thermal conductivity, thermal stability, high electrical resistance and a coefficient of thermal expansion closer to that of the silicon than SiO₂, and so on. For wafer bonding to be successful, the AlN films must be of high quality, be stable, have a smooth surface, and be able to withstand normal silicon device processing conditions. It is believed that such materials can be synthesized by ion-beam-enhanced deposition (IBED) [4–6].

Although, AlN films have been used as buried insulator in BESOI materials by Bengtsson et al. [3], no one has succeeded in fabricating SOI materials taking AlN films as buried layer by the Ion-Cut process and no further research was found. In this paper, AlN films were prepared on Si(1 0 0) by IBED and the films were bonded to a hydrogen-implanted wafer at room temperature using the Ion-Cut technique. Since our interest is on the use of AlN film to fabricate a novel SOI structure, the obtained SOI structure were also characterized.

2. Experimental

2.1. Film deposition

A 100 mm diameter Si(1 0 0) (1–3 Ω) wafers cleaned with a standard RCA procedure were used as the substrates. AlN films were prepared by employing electron beam evaporation of Al and simultaneous bombardment by N-ions. In the IBED system (Eaton Z-2000), an electric-gun was used to evaporate high purity Al (99.999%). The evaporation rate of Al could be adjusted from 0.5 to 5 Å/s, and 0.5 Å/s was adopted in this work as an optimal parameter. A Kaufman ion source was used to produce the N-ion beam. The N-ion beam (60% N₂⁺, 40% N⁺) bombarded the substrate during Al evaporation at an energy of 20 KeV and an ion flux density of 25 μA/cm². Prior to deposition, the base pressure was about 1 × 10⁻³ Pa and the wafers were maintained at 700 °C during implantation. The combination of Al evaporation and N implantation contributed to the final formation of AlN thin films.

The synthesized films were characterized by X-ray diffraction (XRD), X-ray photoelectron spectroscopy (XPS), spreading resistance profiling (SRP), and atomic force microscopy (AFM). XRD studies were performed with a D/max 2550 V diffractometer using Cu Kα radiation. The XPS analysis was done using a Microlab MK II spectrometer using Mg Kα radiation. The C 1s line (284.6 eV) was used for calibration. AFM was conducted to examine the surface topography of the AlN films using a Digital Instrument Nanoscope IIIa.

2.2. SOI structure formation

The Ion-Cut process to fabricate the SOI structure with AlN comprised three main steps:

1) Hydrogen implantation into 4 in. Si wafers (dose = 6 × 10¹⁶ H⁺/cm² and energy = 150 KeV).
2) Hydrophilic bonding at room temperature of the hydrogen-implanted silicon wafer and the AlN wafer, the AlN film acting as the buried dielectric layer in the final SOI structure.
3) Two-phase annealing of the bonded wafers. During the first phase (400–600 °C), the bonded pair split into two parts across the projected range of the hydrogen implant due to coalescence of the buried hydrogen bubbles, giving rise to an SOI structure and a recyclable silicon wafer. After the wafer has been cleaved, high temperature annealing was performed in N₂ ambient at 1100 °C for 1 h.

The resulting SOI structure was investigated by cross-sectional transmission electron microscopy (XTEM) and SRP.

3. Results and discussion

3.1. Synthesis and characterization of AlN film

Although, the main objective of this work was to fabricate SOI structures using AlN as the buried insulator, it must be emphasized that, in the Ion-Cut process, successful bonding strongly depends on the quality of the AlN film. Therefore, deposition of high quality AlN films was a key step in our work.

XRD studies were performed to assess the microstructure of the synthesized films. However, no peaks appear in the XRD pattern (not shown here), suggesting that the film prepared might be amorphous.

XPS studies were carried out to examine the formation of AlN. Fig. 1a shows the binding energy spectra
of Al 2p of AlN film formed at the Al evaporation rate of 0.5 Å/s on Si(1 0 0). The Al 2p peak appears at 73.8 eV as a single peak, which corresponds to the binding energy of the Al 2p state in the Al–N bond, and no free Al peak at the binding energy of 72.8 eV is detected. Meanwhile, in Fig. 1b, a single peak of N 1s appears at 396.6 eV, corresponding to the binding energy of the N 1s state in the N–Al bond. Both of these two peaks confirm the formation of the AlN film and the measured binding energies of the Al 2p and N 1s states agree well with previous reports [7]. As a candidate for the insulating layer in SOI materials, the AlN films must have the correct dielectric properties in order to electrically insulate the overlying silicon layer from the substrate. Therefore, it is critical to examine the electrical property prior to any further work. SRP was employed here to determine the electrical properties and thickness of the films. Fig. 2 depicts the SRP result of the AlN film formed at an Al evaporation rate of 0.5 Å/s. There is a highly resistive layer on the surface with a thickness of about 250 nm with spreading resistance of higher than \(10^8\) Ω (exceeding the measurement range of the SRP apparatus), suggesting excellent dielectric properties of the film. This result is consistent with previous results for nitridation of Al-coated Si substrate [8]. Above a depth of 250 nm, the spreading resistance drops to \(10^3\) Ω (corresponding to Si substrate), indicating a broad the AlN/Si interface and the thickness of this film is approximately 250 nm. The nonabrupt interface between the AlN thin film and the substrate is a consequence of IBED because N-ion implantation adopted in this technique results in an approximate Gaussian distribution of the implanted N atoms.

In addition to macro uniformity (evidenced by the final successful bonding), the AlN should have a small microroughness to meet the strict requirement of bonding. Fig. 3 shows the AFM image of the films synthesized at an Al evaporation rate of 0.5 Å/s. It can be observed that the surface of the AlN film is smooth and uniform, and the surface roughness rms values are 0.13 nm that is good enough for direct bonding without additional polishing procedures.

### 3.2. Formation of SOI structure with AlN buried layer

The main steps of fabricating the SOI structure by means of Ion-Cut has been described in the Section 2.
The AlN thin film with a thickness <100 nm was deposited at an Al evaporation rate of 0.5 A˚/s. The AlN wafer was successfully bonded to a hydrogen-implanted silicon wafer in a micro-cleanroom at room temperature. Fig. 4 shows the cross-sectional TEM micrograph of the bonded structure giving direct evidence of the formation of SOI. The thickness of top Si is about 1.2 μm that is consistent with that calculated from TRIM-96. The TEM results show that the buried AlN layer is continuous. High resolution XTEM micrograph reveals the microstructure of the interfaces between the top Si/AlN buried layer (upper interface, shown in Fig. 5a) and AlN/Si substrate (below interface, shown in Fig. 5b). It can be seen that the upper interface is very straight and smooth, originating from the surfaces of AlN film and H-implanted Si. The top silicon layer has good crystallinity with no detectable defects. The spot diffraction pattern of selected-area electron diffraction (SAD) also confirms good crystallization of the top Si. However, the bottom interface indicated in Fig. 5b is not as smooth as the upper one due to energetic N-ion bombardment during IBED. The structure of the AlN layer is amorphous and consistent with the result of XRD.

SRP was used to characterize the resulting SOI structure, and the results are exhibited in Fig. 6. Three layers including the top silicon layer, buried AlN and substrate, can be clearly distinguished. The spreading
The resistance of the top Si is uniform and about $2 \times 10^4 \, \Omega$, indicating its uniform electrical properties. The very steep slope from the top silicon layer to buried AlN at the depth of 1.25 µm in the spreading resistance profile implies a sharp interface between the overlying silicon and AlN. The silicon thickness measured by SRP is about 1.25 µm and similar to XTEM result. The most striking observation is that the buried AlN layer exhibits a high resistance ($>10^8 \, \Omega$) in spite of a high temperature annealing step. This verifies its high heat endurance and compatibility with high temperature device processing.

Fig. 5. High resolution XTEM image of (a) top Si/AlN buried, and (b) buried AlN/substrate Si interface of the SOI structure.

Fig. 6. Spreading resistance profile of the SOI structure using AlN film as buried layer.
4. Conclusion

We have successfully synthesized AlN films on 100 mm Si(1 0 0) substrate using IBED. The film deposited at the Al evaporation rate of 0.5 Å/s has a smooth surface and excellent dielectric properties, is suitable for the dielectric buried layer in SOI material. Using the Ion-Cut technique, the AlN sample was bonded successfully to a H-implanted silicon wafer at room temperature. XTEM micrographs confirm the formation of the SOI structure. The top Si layer has good crystallinity as well as electrical properties, as disclosed by high resolution XTEM image and SRP results.

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