Study of tungsten deposited on amorphous Si, Si (111) and SiO_2 using direct-current magnetron sputtering

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Abstract. Tungsten (W) commonly serves as the electrode layer or acoustic reflector layer for the highly columnar growth of AlN piezoelectric thin films used to fabricate film bulk acoustic resonators in power applications. The structure of W film directly influences the texture of AlN thin films above. Moreover, the surface morphology and texture of W thin films are influenced by the substrate materials. In this study, the effects of different underlays on the characteristics of W films deposited using direct-current magnetron sputtering are compared. The results show that W thin film deposited on SiO_2 has well-orientated crystallization, dense microstructure, the smallest RMS and the lowest electrical resistivity. W thin film deposited on Si (111) has the worst RMS and electrical resistivity but a common residual stress and crystallization. W deposited on amorphous Si (α-Si) presents column-like microstructure, the lowest residual stress but a common RMS and electrical resistivity. Since the substrate materials have direct impacts on the resonators it is necessary to take these impacts into account during the design stage of filters or sensors based on film bulk acoustic resonators.

Introduction

Tungsten (W) has many excellent properties such as high melt temperature near 3673K, high mechanical strength, fine pattern ability, good metal barrier performance, high thermal and chemical stability. Due to these properties, W has attracted much attention as a promising material in many applications, such as thermal emission sources for energy harvesting applications [1], interconnect material of choice for semiconductor metallization [2], short wavelength emitters [3], and thin film bulk acoustic wave resonators (BAWs) for radio frequency microelectromechanical systems (RF-MEMS) applications [4]. Among these applications, BAW devices consist of an AlN film sandwiched between metal electrodes. To enhance the performance of BAWs highly c-axis oriented texture of AlN thin films are required to obtain high effective eletromechanical coupling coefficient. Moreover, flat surfaces of each layer in the devices are also needed to prevent the acoustic wave scattering loss [3]. The quality of AlN thin film is mostly influenced by the surface characteristics and texture of the substrate apart from the sputter deposition parameters. The favorable texture for the deposition of highly c-axis oriented AlN thin films on metals with a cubic structure appears to be (111), such as Al (111), Pt (111) and Au (111), because of the lattice match [5,6]. Unfortunately, these metals are unsuitable to be the electrode layer of BAW resonators because of low acoustic impedance of Al, hard etching resistance of Pt and Au [6,7]. W has low acoustic attenuation and small mismatch in the thermal expansion coefficient with AlN. Its high melt temperature enables the resonators to have high power handling abilities. Moreover, its high acoustic impedance compare with AlN makes the acoustic energy to be confined in the resonators [8]. These features make W a suitable electrode for BAW resonators and extend their application to high power handling field. The influence of sputtering conditions on the properties of W thin films has been systematically researched [9-12]. The AlN films deposited on W have also been widely studied [13-15]. However, to authors' knowledge different substrates which have a direct influence on the qualities of W thin films are seldom studied. The impacts of different commonly used substrates on sputtered W should be identified to determine the most suitable choice and optimize the performance of BAW resonators.

In this study, commonly substrates of α-Si, Si (111), SiO_2 were selected for the sputtering of W thin film. The microstructure, surface morphology, residual stresses and electrical resistivity of W thin films deposited on these underlays were researchedand compared.

Experiments

Two-inch Si (111) wafers were conventionally cleaned using a standard procedure. The wafers were oxidized at 1100°C in wet O_2 for 30 minutes to obtain a 500 nm SiO_2 film. An α-Si film was then deposited on the substrate using e-beam thermal evaporation. The substrates including α-Si layers, the cleaned Si (111) wafers and thermal coated SiO_2 which were used in this paper were prepared after the aforementioned process. W thin films were deposited by direct-current (DC) magnetron sputtering in Ar atmosphere. The purity of W target is 99.95%. The deposition chamber was pumped down to a background pressure of 5×10^{-4} Pa and the working pressure was 2 Pa. The Ar gas flow rate was fixed at 20 sccm. The sputtering power was 25 watts. The distance between the target (2 in) and the substrate was 60 mm. The W target was pre-sputtered for 5 minutes. The W thin films were deposited for 13 minutes. The X-ray diffraction (BEDE D1 System) with CuKα radiation was used to investigate the crystalline structure of W thin films. The surface morphology and the root mean square (RMS) surface roughness were determined by the atomic force microscopy (AFM, a SEIKO Instruments SPA300HV). Field emission scanning electron microscopy (Inspectf, FEI) was utilized to observe the cross-sectional morphologies. The profilometer (Dektak 150) was used to determine the residual stress of W thin films by measuring the wafer curvature change. The four-point measurement (Four Dimensions 280 DI) was used to determine the electrical resistivity of W thin films.

Results and Discussion

The XRD patterns of W thin films sputtered on α-Si, Si (111) and SiO_2 are presented in figure 1. Two main W peaks including W (200) peak and W (110) peak are observed. The amplitudes of W (200) peaks on α-Si and Si (111) are almost the same, but higher than that of W (200) peak on SiO_2. Besides, the amplitudes of W (110) peaks on the three substrates show no difference. In this research, the SiO_2 and α-Si films are both in amorphous state. The amorphous films will promote the crystallinity of the films deposited on them. The effects of the amorphous layer are also reported by other researchers [16,17]. The amorphous layer can reduce the lattice mismatch and provides nucleation sites for the growth of oriented crystalline films on it [18, 19]. Besides, the substrate surface of α-Si was rougher than that of Si (111) and SiO_2 in this study. At low sputtering power, the W atoms are lack of surface mobility. They adhered to where they impinged. Thus the incident W atoms moved relatively further on the SiO_2 surface than which on α-Si surface resulting in better

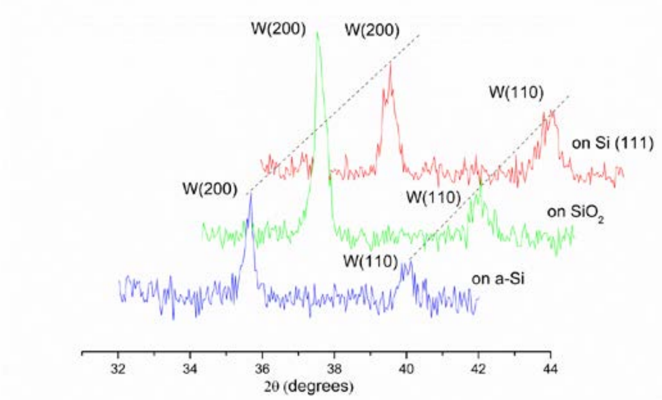

Fig. 1. X-ray diffraction patterns of W thin films deposited on different substrates using DC magnetron sputtering

crystal structure. This result indicates that the W films on SiO_2 have better W (200) crystal orientation than that on Si (111) and α-Si.

The surface morphologies of W films deposited on different substrates were characterized by the AFM images in figure 2. The corresponding RMS and deposition rate of W films were shown in figure 3. It is found in figure 2 that many small W grains grew on the Si (111) and α-Si. Besides, the W films on the Si (111) and α-Si are also porous. These results are because that the incident W atoms are lack of kinetic energy. Thus the W atoms nucleated where they impinged and they can not grow into large islands which lead to small grains and high grain densities. Moreover, comparing with W grains on Si (111) and α-Si, the W grains on SiO_2 are relatively larger. This result is consistent with XRD observations that the W film on SiO_2 have better crystal orientation than that on Si (111) and α-Si. Figure 3 shows that the W films deposited on SiO_2 have the smallest RMS and deposition rate among the three substrates. There is little difference of RMS and deposition rate of W films sputtered on Si(111) and α-Si, respectively. The W films deposited on SiO_2 have denser microstructure compared with W films deposited on either Si (111) or α-Si, which leads to low deposition rate. Meanwhile high deposition rate of W films on Si (111) and α-Si tends to have more lattice defects which are frozen in during deposition resulting in rough surface. These results are in accord with following SEM observations.

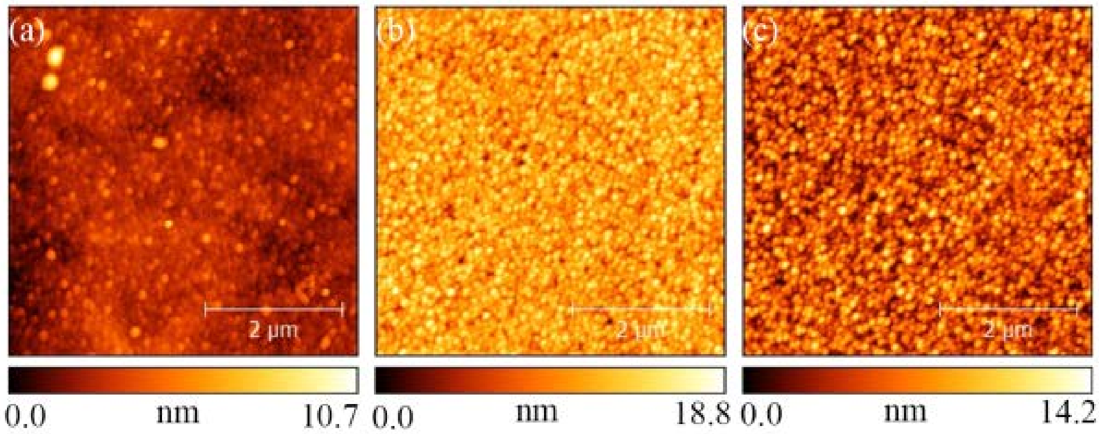

Fig. 2. AFM images for W thin films deposited on (a) SiO_2, (b) Si (111), (c) α-Si

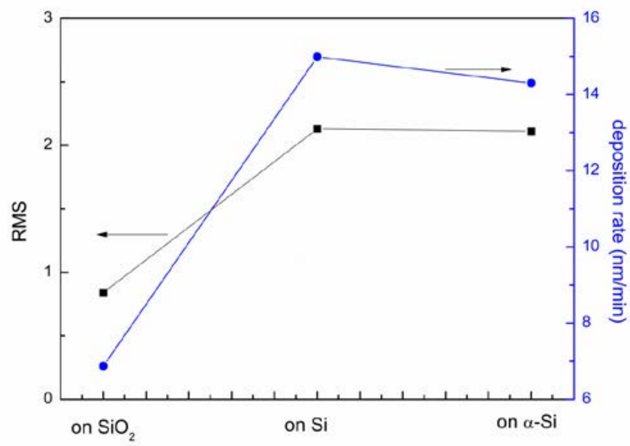

Fig. 3. RMS and deposition rate of W thin films sputtered on different substrates

To characterize W films` microstructures, the cross-sectional views of SEM images of W films on the three substrates are shown in figure 4. The W films deposited on SiO_2 are compact and dense. While on Si (111) the microstructure of W films is porous with many clusters and grain boundaries. Moreover, the W films sputtered on α-Si have porous and column-like microstructure. The W films deposited on SiO_2 are the thinnest among the three substrates. The more-domed tops of W films on Si (111) and α-Si indicate rougher surface corresponding to AFM observations. In this study, the kinetic energy of W atoms is low leading to low surface mobility. As aforementioned discussion the W atoms on SiO_2 are more likely to form better crystal orientation and limit the number of lattice defects that are frozen in during sputtering comparing with which on Si (111) and α-Si. Thus, the W films on SiO_2 are compact while W films on Si (111) and α-Si is porous, imperfect and relatively thicker under the same deposition conditions.

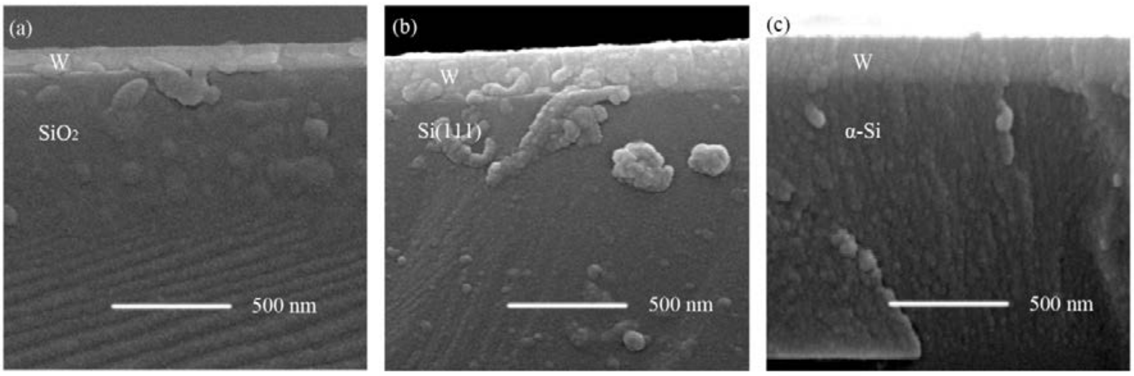

Fig.4. Cross-sectional view of SEM images for W thin films deposited on (a) SiO_2, (b) Si (111), (c) α-Si

All the residual stresses of W films deposited on SiO_2, Si (111) and α-Si are of the tensile type as shown in figure 5. The tensile stress is because of the absence of energetic particle bombardment at relatively high pressures due to more scattering events in the sputtering-gas region [20]. The W film on α-Si has the lowest stress of 543MPa. While on SiO_2 W film has the highest stress of 888MPa. The W film on Si (111) has the stress of 822MPa slightly lower than that on SiO_2. The residual stress is related to lattice mismatch between film and substrate, thermal expansion and the substrate surface roughness [5, 21, 22]. The linear thermal expansion coefficients of SiO_2, Si, and W are 0.5, 2.6 and 4.5, respectively. W has more different thermal expansion coefficient with SiO_2 compared with Si and α-Si, inducing highest stress among the three substrates under the same deposition conditions. Besides, the α-Si can reduce the mismatch between W. Thus the mismatch between W and α-Si is smaller than that between Si (111) and W leading to lower stress of W films on α-Si.

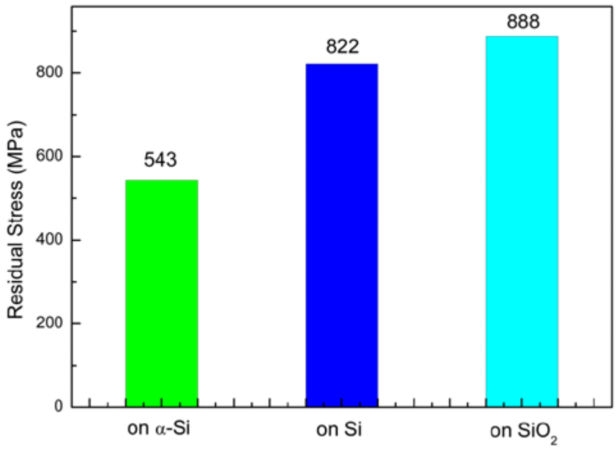

Fig. 5. Residual stress of W thin films deposited on different substrates

The electrical resistivity of W films deposited on the three substrates is shown in Figure 6. The W film on SiO_2 has the lowest electrical resistivity of 72.74 μΩ•cm. While on Si (111) W film has the highest electrical resistivity of 166.83 μΩ•cm. The W film on α-Si has the electrical resistivity of 161.5 μΩ•cm slightly lower than that on Si (111). These effects are consistent with aforementioned observations. The W films on SiO_2 have dense microstructure while W films on Si (111) and α-Si are porous and more scattering occurred at the grain boundaries leading to the electrical resistivity increase. Moreover, W films on Si (111) and α-Si have the similar surface profile and microstructure, and show similar electrical resistivity.

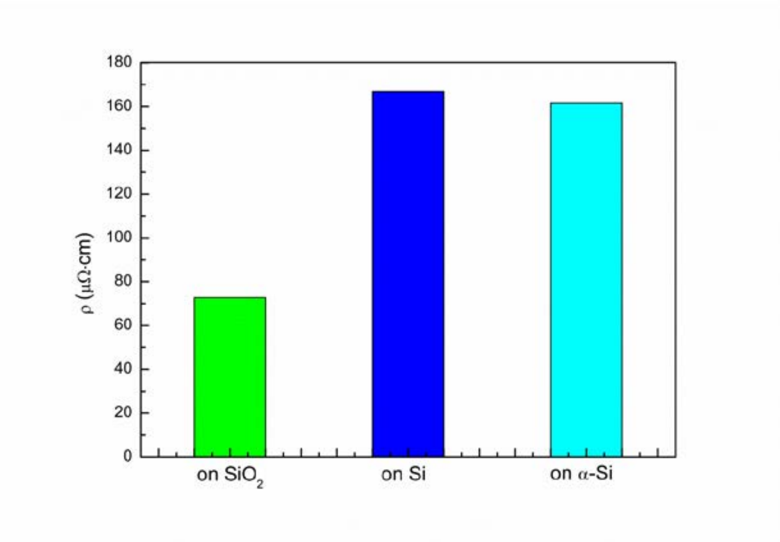

Fig. 6. Electrical resistivity of W thin films deposited on different substrates

Conclusion

In this study, the characteristics of W films which were deposited using DC magnetron sputtering on SiO_2, Si (111) and α-Si under the same conditions were demonstrated. In general, the W film deposited on SiO_2 presents relatively good properties, including well-orientated crystallization, dense microstructure, the smallest RMS of 0.84nm and the lowest electrical resistivity of 72.74 μΩ•cm. The W film on α-Si shows the lowest residual stress of 543MPa but a common RMS and electrical resistivity. The W film on Si (111) has the worst RMS and electrical resistivity but a common residual stress and crystallization. According to this study, different substrates have direct impacts on the W thin films which are used as electrode layers or acoustic reflector layers in BAW resonators. Therefore, it is necessary to take substrate materials into account during the design stage of BAW filters or sensors based on BAW resonators.

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