[논 문] 한국재료학회지
Korean Journal of Materials Research
Vol. 8, No. 11 (1998)

RF Power Dependence of Stresses in Plasma Deposited Low Resistive Tungsten Films for VLSI Devices

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고집적 소자에 적용되는 저저항 텅스텐 박막에서 응력의 RF power의존성

이창우 · 고민경 · 오환원 · 우상록 · 윤성로 · 김용태 · 박영균 · 고석중
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(1998년 6월 5일 받음, 1998년 8월 17일 최종수정본 받음)

초 록 Si 기판의 온도를 200에서 500℃까지 변화시켜가면서 고집적 소자의 금속배선으로 응용되고 있는 저저항의 텅스텐 박막을 플라즈마 화학증착 방법에 의해 제작하였다. 이렇게 증착된 텅스텐 박막의 비저항은 H_2/WF_6 가스의 분압비에 따라 매우 민감하게 작용하는 것을 알 수 있다. 플라즈마 밀도가 0.7W/cm^{2}이하에서는 박막내에 존재하는 잔류응력이 2.4×10^9dyne/cm^2 이하이다. 그러나 1.8에서 2.7W/cm^{2}로 증가함에 따라 잔류응력은 8.1×10^9에서 1.24×10^{10}dyne/cm^{2}로 갑자기 증가하는데 이는 박막을 증착할 때에 플라즈마 밀도가 증가하면 이온이나 radical bombardment의 영향 때문이다.

Abstract Controlling the wafer temperatures from 200 to 500℃, low resistive tungsten thin films used for VLSI metallization are deposited by PECVD method. Resistivities of plasma deposited tungsten thin films are very sensitive to the H_2/WF_6 partial pressure ratios. Residual stress behaviors of the films as a function of plasma power density were also studied. At the power density under the 0.7W/cm^2, residual stress of W film is about 2.4×10^9dyne/cm^2. When the power density is, however, increased from 1.8 to 2.7W/cm^2, residual stress is suddenly increased from 8.1×10^9 to 1.24×10^{10}dyne/cm^2 due to the ion or radical bombardment at high power density.

1. Introduction

Several difficulties, such as junction spiking, hillock, lateral diffusion, and electromigration, are encountered by using the aluminum-based alloy in metal to silicon ohmic contact structures for very large scale integrated (VLSI) devices.[1)] Contact layers and diffusion barriers must be inserted between Al and heavily doped Si in the source/drain regions of metal oxide semiconductor (MOS) transistors to reduce the contact resistance and to ensure the metallurgical integrity of the contact structures during subsequent heat treatments. Refractory metals such as tungsten or molybdenum having a work function close to the midgap of Si and having low resistivity that would appear to be suitable candidates to act as contact layers and diffusion barriers simultaneously.[2)]

In addition, plasma enhanced chemical vapor deposition (PECVD) of W thin films by reduction of tungsten hexafluroide (WF_6) has been an attractive method of metallurgical technology such as contact diffusion barriers, via fill, and multilevel metallization. And also PECVD looks attractive, as it can provide low temperature processing, excellent step coverage, and high quality films.[3~5)]

Therefore, we have concentrated on the characterization of the LPCVD and PECVD-W thin films grown with WF_6-H_2 mixture for H_2 reduction process or with WF_6-SiH_4-H_2 mixture for silane reduction process while the wafer temperatures are varied from 200 to 500℃. We have also investigated residual stresses of PECVD-W thin films which are dependent on the rf power density.

In a cold wall CVD reactor, wafer temperature was dependent on many parameters such as the temperature of the hot plate, the composition of the gas mixture, the pressure of the reactor, the distance between the wafer and the hot plate, the distance between the electrodes, and the emissivity of the substrate, etc. These parameters were usually varied during the deposition process, and the differences of the thermal resistance between the hot plate and the Si wafer were occurred. Thus the wafer could lead quite erroneous results to the actual wafer temperature.[6,7] Therefore, the conventional pyrometer or thermocouple readings made the temperature control unstable, i.e., the temperature reading was critically dependent on the emissivity of pyrometer, and varied with the exposed materials, wafer doping, and surface condition of wafer, etc. In addition, if the signal of the thermocouple which was contacted to the hot plate was used for temperature control, which might lead significant errors since the heat transport between hot plate and Si wafer depends on the above-mentioned parameters.[7] In our case, in order to measure the actual wafer temperature, 0.01 in. Chromel-Alumel (90% Ni-10% Cr vs 95% Ni-2% Mn -2% Al) thermocouple was installed into the small cavity (width : 1mm, depth : 400㎛) in the monitoring silicon wafer and the cavity was sealed with ceramic bond. The thermocouple lines were encapsulated with metal tube to get rid of rf noise and the metal tube was grounded.[8] The wafer temperatures were measured by two thermocouples bonded with two monitoring wafers, respectively. One of the thermocouples was used for the temperature control and the output signal of the other one was measured by a digital voltmeter. We have investigated the wafer temperature with or without rf power and metal tube and then, there were no differences in the wafer temperatures. In comparison with the properties of LPCVD-W films, a deposition process was carried out under the equivalent conditions of PECVD-W excepting rf plasma.

2. Experimental

Substrates were phosphorus-doped (100) oriented Si wafers with resistivities of 5-6 Ω-cm and were cleaned and spin-dried. Deposition of W films was carried out with a home made parallel type cold wall PECVD reactor [SCP-300-6s, Samhan Co.] and reactant gases were WF_6, H_2, SiH_4. The rf power density was 0.3-3.5W/cm^2. The H_2/WF_6 partial pressure ratios were varied from 4 to 25 and SiH_4/WF_6 partial pressure ratio was maintained at 1.0 while WF_6 partial pressure was fixed at 2×10^{-2}Torr. The total pressure was maintained at 5×10^{-1}Torr by controlling a throttle valve.

3. Results and Discussion

Fig. 1 shows the temperature deviation as a function of pressure and wafer temperature. In the top x-axis of Fig. 1, it shows the temperature deviation between the wafer and the hot plate temperatures in H_2 plasma ambient as a function of reactor pressure. This figure shows that the difference between the wafer and the hot plate temperatures is varying from 140 to 44℃ as total pressure of the reactor is varying from 9×10^{-3} to 9×10^{-1}Torr. When the total pressure of H_2 is decreased, the hot plate temperature must be increased in order to maintain the wafer temperature at 250℃ because the heat transport from the hot plate to the silicon wafer is more difficult at lower pressure. In addition, as shown in the bottom x-axis of Fig. 1, it is found that at the fixed total pressure of 0.5 Torr, the difference between the wafer and the hot plate temperatures increases from 50 to 130℃ while the wafer temperature varies from 250 to 450℃. We also measured the rf induction heating effect when the total pressure was varied from 0.09 to 1 Torr, the wafer temperature measured with rf discharge was higher than the temperature measured without rf discharge by 5-7℃. Thus we concluded the induction heating by the rf power was negligible. Therefore, the deposition temperatures of all processes of LPCVD and PECVD were determined by the wafer temperature. The H_2 reduction and the SiH_4 reduction processes for the subsequent growth of W

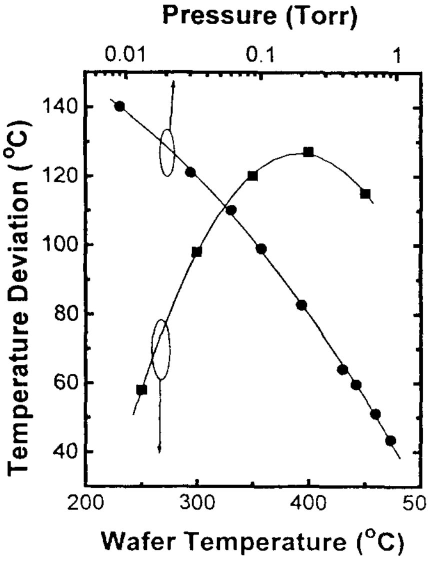

Fig. 1. The difference between wafer temperature and hot plate temperature in H_2 plasma ambient as a function of (a) wafer temperatures at the total pressure of 0.5 Torr, (b) total pressures.

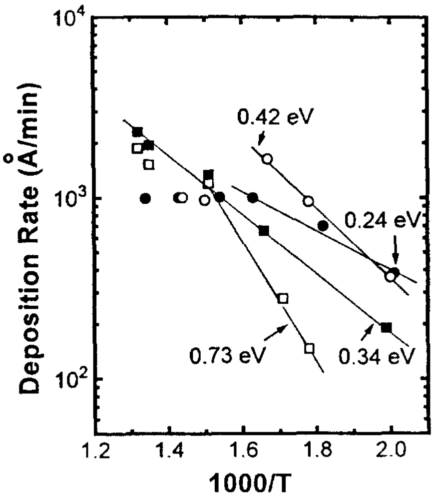

Fig. 2. Arrhenius plot of deposition rate between LPCVD and PECVD-W vs reciprocal temperature grown on Si (a) at the H_2/WF_6 input ratio of 25 (H_2 = 100sccm), (b) at the SiH_4/WF_6 ratio of 1 (H_2 = 100sccm). (□, ■ : H_2-reduction process ; ○, ● : SiH_4-reduction process ○, □ : LPCVD ; ●, ■ : PECVD)

thin films on the Si surface requires activation energies. Thus, activation energies for W deposition of LPCVD and PECVD were investigated by plotting the logarithm (deposition rate) as a function of temperature reciprocal as shown in Fig. 2. In the Arrhenius plots of H_2 reduction process, two different regimes can be seen in LPCVD, and the activation energies obtained from the slopes for LPCVD (hollow square) and PECVD-W (solid square) are 0.73 and 0.34 eV, respectively. In the LPCVD process, two different regimes can be seen, that is, a regime showing a strong temperature dependence and the other regime showing a slight dependence on temperature. The regime showing strong temperature dependence is known to be controlled by the surface reactor rate,[9] while the region showing the slight dependence on temperature is controlled by the rate at which the reactant is supplied to the substrate.[9] The break point showing two different regimes of LPCVD-W is about 400℃ and is a function of the WF_6 partial pressure.

On the other hand, in the PECVD-W, only one regime can be seen. For SiH_4 reduction process, the activation energies obtained from the slope of logarithm (deposition rate) for LPCVD (hollow circle) and PECVD-W (solid circle) are 0.42 and 0.24 eV, respectively.

Comparing the activation energies for LPCVD-W grown with WF_6-H_2 and WF_6-SiH_4-H_2 systems, it is found that the activation energy of 0.42 eV for WF_6-SiH_4-H_2 system is apparently lower than 0.73 eV for WF_6-H_2 system. In the case of PECVD-W, the activation energy decreases from 0.34 to 0.24 eV with the addition of SiH_4. This means that the Si on W reacts with WF_x more actively than the atomic hydrogen, and W deposition will occur rapidly in silane reduction process. And the deposition rate of PECVD-W thin film is faster than that of LPCVD. Thus, we only use the PECVD method. In contrast with the LPCVD-W thin film process, the characteristics of PECVD-W thin films strongly depend on the complicated plasma process. It is found that the resistivity of PECVD-W is strongly dependent on the H_2/WF_6 partial pressure ratios, while the resistivity of LPCVD-W is insensitive to the H_2/WF_6 partial pressure ratios. And several techniques using various combinations of reactant systems and/or deposition temperature have been tried to avoid the encroachment; for example, silane reduction process has been proposed to avoid encroachment.[10]

However, the selectivity in silane reduction process was strongly dependent on the SiH_4/WF_6 partial pressure ratios, and perfect prevention of the Si consumption was impossible on the initial deposition stage, because high surface concentration of F could not be removed until WF_6 interacts with SiH_4 and F atoms were removed exclusively as SiF_4. Thus, we were concentrated only on H_2 reduction process. In order to study the effects of film stress on resistivity, rf power densities were varied from 0.35 to 3.5W/cm^2, since the stress of thin film strongly depends on the rf power density.[11] Therefore, the resistivities of PECVD-W films grown on Si as a function of rf power density were investigated as shown in Fig. 3.

Resistivities were 10-15$\mu\Omega$-cm when the rf power density was lower than 1.7W/cm^2. When the rf power

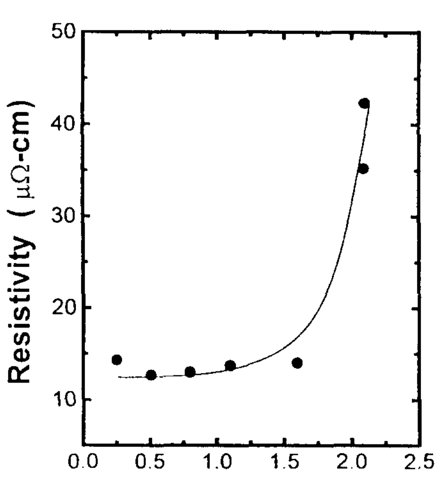

Fig. 3. Resistivities of PECVD-W on Si as a function of the plasma power density.

density, however, was higher than 2W/cm^2, resistivities were exponentially increased and the W films deposited at the rf power density over 3W/cm^2 were delaminated by themselves just after the deposition process. This indicates that the quality of PECVD-W films could be deteriorated due to the high energetic ion bombardment. Cruzan et al.[11] reported that the electrical resistivity of sputtered W thin films were strongly dependent on the radiation damage, which was the origin of the film stress at the interface of W film and substrate. Therefore, the evidence for the relation between the stress and the resistivity of W film was confirmed with the measurement of film stress with varying the rf power density.

Residual stress of as-deposited W film is measured by the x-ray method as follows : the internal stress in W film is determined by the two-exposure method[11,12] where the interplanar distance d, is determined at angular orientations, $\pm\psi$, to the surface direction. The measurement procedure consists of determining the d_o spacing parallel to the surface at $\psi = 0°$, and subsequently determining d_ψ values at ψ rotations ±10, ±20, ±30, ±40°, oblique to this direction. The d values are related to the stress by the following expression :

$\sigma_f = \frac{d_\psi - d_o}{d_o} \cdot \frac{E}{(1-\nu)} \cdot \frac{1}{\sin^2\psi}$, where d_ψ is the interplanar spacing at an angle ψ with respect to the sample surface. E is the average Young's modulus of W ($=4.11 \times 10^{12}$dyne/cm^2) and ν is the poisson's ratio and the value is 0.38. Average residual stress is measured macroscopically by this technique. The (110) peak of W occurring at 40.2° is found to be sharp enough for this measurement. Thus, the stress of W film is determined by the slope of $\frac{d_\psi - d_o}{d_o} \cdot \frac{E}{(1-\nu)}$ vs $\sin^2\psi$ as shown in Fig. 4.

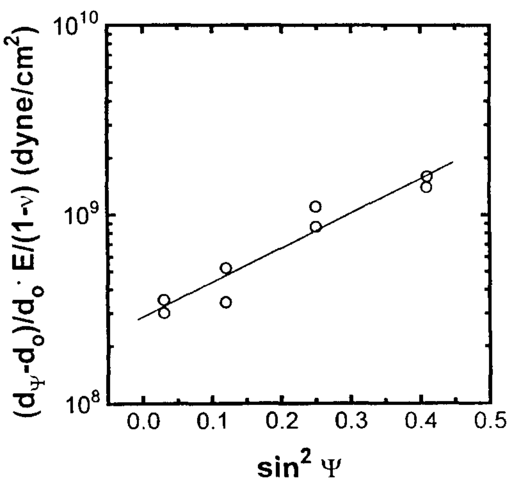

Fig. 4. Typical result of stress measurement of PECVD-W on Si through X-ray diffractometer.

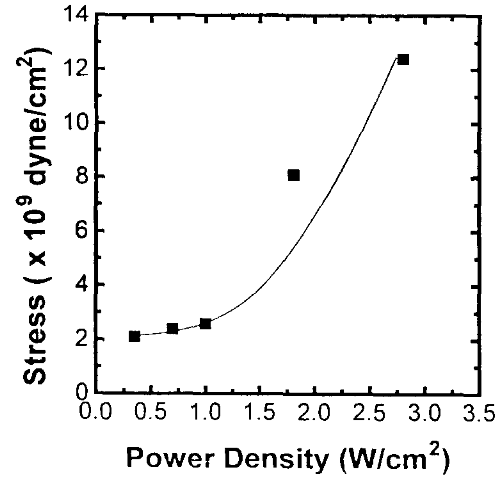

Fig. 5. Stresses of PECVD-W on Si as a function of the power density.

Fig. 5 shows the variation of stresses of PECVD-W films on Si as a function of power density. At the power density of 0.7 W/cm^2, the residual stress of W film is about 2.4×10^9dyne/cm^2. But when the power density is increased over 2W/cm^2, the residual stress is suddenly increased from 8.1×10^9 to 1.24×10^{10}dyne/cm^2. Consequently, it can be concluded that the resistivity is deteriorated due to the ion or radical bombardment at the high power density.

4. Conclusions

We have obtained more conductive PECVD-W thin films with controlling the wafer temperature instead of the hot plate temperature. And also we have studied the stress behaviors as a function of plasma power density. At the power density under the 0.7W/cm^2, the stress of W film is about 2.4×10^9dyne/cm^2. But when the power density is increased from 1.8 to 2.7W/cm^2, the stress is suddenly increased from 8.1×10^9 to 1.24×10^{10}dyne/cm^2 due to the ion or radical bombardment at the high power density.

Acknowledgement

This work was financially supported by the Korea Sanhak Foundation in 1997.

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