EFFECT OF COMPRESSION PLASMA FLOW ON STRUCTURE-PHASE TRANSFORMATIONS OF TANTALUM-SILICON SYSTEM

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1. Introduction

The performance of a heat source is an important issue for more precise and controllable material processing. In this connection, a pulsed plasma source is one of the most superior heat sources due to its high temperature and high energy density transmitted to target. A quasistationary plasma accelerators are sources of supersonic compression plasma flows in which the duration of the stable state is much longer (~100-1000 μs) than the flight time of the plasma in the acceleration channel. Magnetoplasma compressor (MPC) is the source of quasistationary compression plasma flows (CPF) [1]. The action of CPF on metals and semiconductors intensively studied for last decade promote CPF as an effective tool for materials modifying [2]. The thermal, radiation and mechanical action of the plasma flow provides non-equilibrium conditions for the formation of low-dimensional structures on the materials surface and in pre-surface layers [3]. The CPF can be effectively used for mixing of 'coating/substrate' system, thus leading to alloying of substrate with atoms of coatings and a plasma forming gas. On the other hand, metal silicides are widely used in electronics due to their compatibility with silicon technology and wide variety of electrophysical properties subject to element composition, stoichiometry and crystal structure [4].

2. Experiment

Single crystal silicon wafers (crystallographic orientation of both (100) and (111)) were used as substrates. Pre-deposition of Ta was carried out by ion beam sputtering and deposition technique. The method was new generation of protective coating by using an ion source that can generate two separate ion beam with ring geometry. One of them is used for sputtering, the other for pre-treatment (ion cleaning and activation) of the substrate surface before coating [5]. Resulting layer thickness was 2 μm. CPF treatment was carried out in magnetoplasma compressor (MPC) of compact geometry (fig. 1). CPF was performed in "residual gas" mode: pre-vacuumed compressor chamber was filled with orifice gas (nitrogen) up to 400 Pa pressure. Samples were fixed in a distance of 12 cm to cathode, were exposed to CPF by single and by series of three pulses.

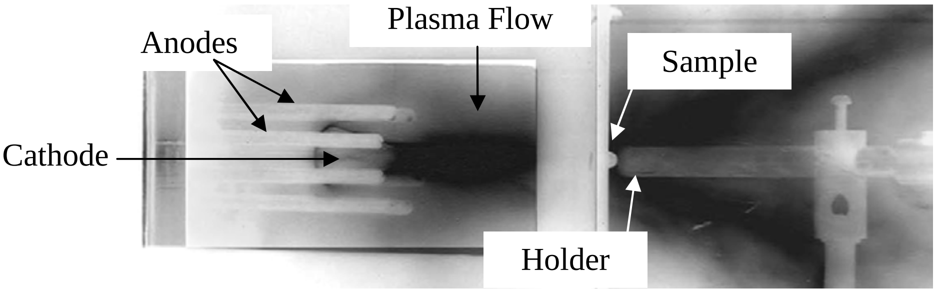
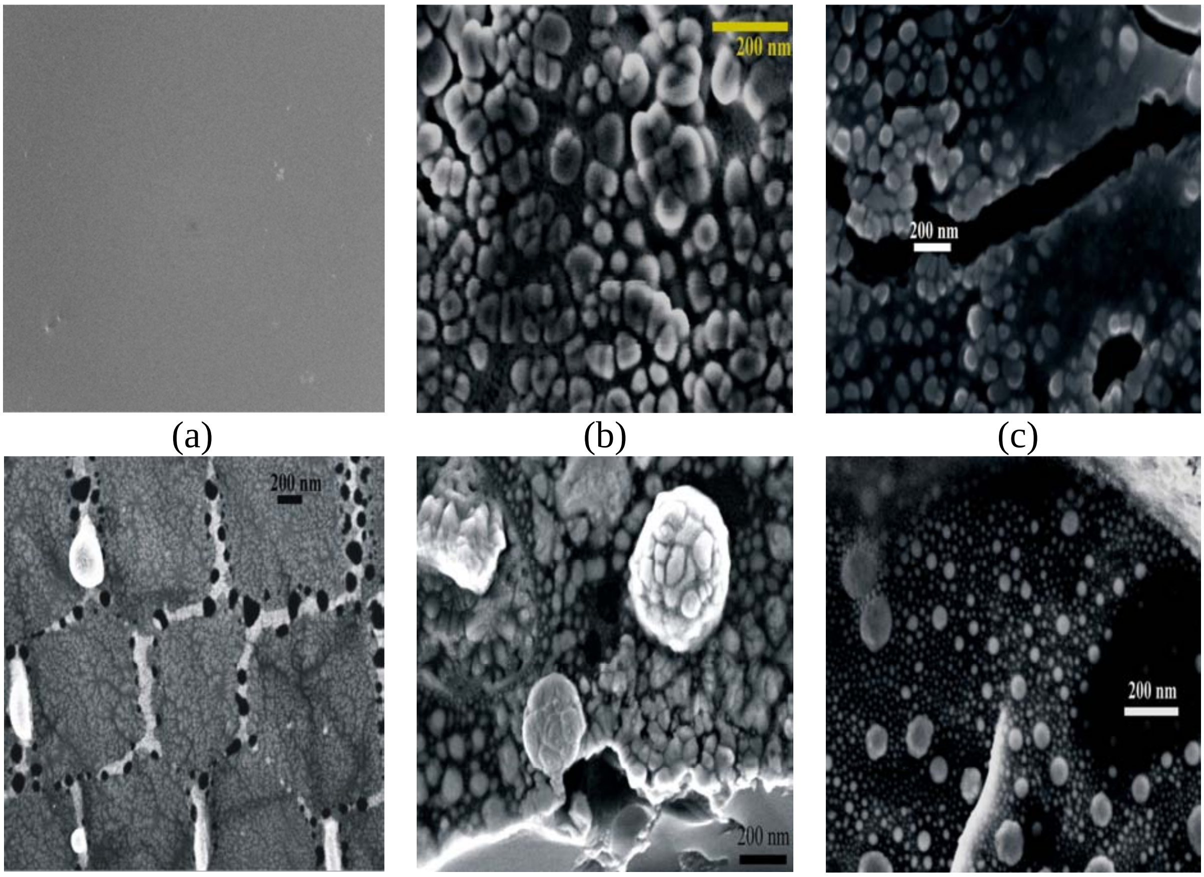


Figure 1. Photo of Compression plasma flow (CPF) system during a typical experiment.

The plasma flow parameters were as follows: pulse duration ~100 μs, plasma velocity $(5\text{-}6)\times10^6$ cm/s, electron concentration $(4\text{-}7)\times10^{17}$ cm^{-3}, dynamic plasma pressure and temperature 1.5 MPa and 2-3 eV, respectively. Power density absorbed by the target W varied in the range from 0.3 to 1.4 GW/m^2. Plasma power density W was controlled by the variation of discharge voltage (2.5–3.8 kV). Phase composition was studied by X-ray diffraction (XRD) using a diffractometer DRON-4-13 with a Bragg–Brentano focusing in Cu emission. Microstructure and elemental composition of the intermixed solidified layer were investigated by scanning electron microscopy (SEM) Supra 55 (Carl Zeiss, Germany) with microanalysis system INCA350 (Oxford Instruments).

3. Results and discussion

The weight percentage of elements after tantalum thin film deposition obtained using EDX (Ta: 81.7%, O: 11.5%, W: 4.6% and Ag: 2.3%). The SEM image of samples' surface before and after CPF action are demonstrated in figure 2 (a) to (f).The SEM images showed the formation of nano-size silicides particles and clusters (~20 nm to 100 nm). According to phase diagram of Ta/Si system [6], when we reach to silicon melting temperature, Ta has also melted. But this melting occurs in a thin layer and allows to a part of tantalum at the interface to intermixed with silicon. The rest of Ta can be partially evaporated to the shock layer of plasma flow and forced back toward the sample surface. The same phenomena was observed when metallic powder injected to CPF and such nano-scale clusters formed on the target [7]. The other observation was Ta etching at the surface. When melted silicon begins to solidify on the substrate, it receives orientation of the substrate. During solidification of this layer, Ta is etched out of the surface. The formation of this structure is caused by thermal action of plasma. The CPF action leads to heating of the surface layer and initiates solid-state diffusion of metal into silicon followed by rapid cooling (~10^7 K/s) of the intermixed liquid [2]. The dark spots in the grain boundaries (fig 2.d) detected as carbon which may cause by the role of nitrogen atoms at the surface. Figure 3 shows the results of x-ray diffraction analysis of untreated and CPF treated samples. The XRD analysis revealed that crystalline tantalum silicides (mostly in the form of hexagonal $Si_{1-x}Ta_{3+x}$) have been formed for both silicon substrates. This was also confirmed by SEM elemental image map analysis for both one pulse and three pulses of CPF treated samples.

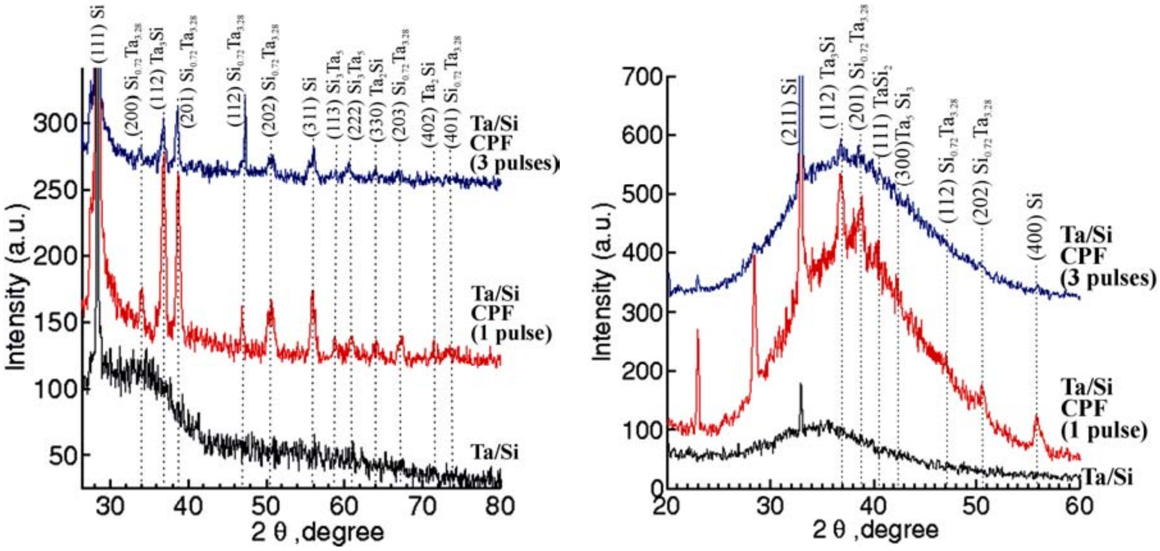


(a) (b) (c)

(d) (e) (f)

Figure 2. SEM images of Ta/Si samples (a) before CPF treatment, after one pulse of CPF on (b) Ta/Si(111), (c) Ta/Si(100) and (d to f) after three pulses of CPF on Ta/Si(100).

In figure 3.b, some amorphous phase has also formed where a wide halo can be seen in XRD patterns of CPF treated samples in 2θ=25-55° region. Average interatomic distance r in the amorphous phase was calculated by Erenfest formula ($2r\sin\theta=1.23\ \lambda$, where θ – diffraction angle, λ - X-ray radiation wavelength). According to the calculation results, by increasing the number of pulses from 1 to 3, average interatomic distance (r) slightly changes from 2.94 Å to 2.89 Å.



(a) (b)

Figure 2. XRD diagram of untreated and CPF treated of Ta/Si system by one and three pulses for (a) Si (111) and (b) Si (100) substrates.

Conclusion

The use of CPF on Ta/Si system results in the formation of metal coating composed from spherical clusters and nanostructures (~20 to 100 nm). Metal and silicon intermixing via CPF action results creation of tantalum silicides. The tantalum silicides mostly are in the form of hexagonal $Si_{1-x}Ta_{3+x}$ and have been created for both Si(111) and Si(100) substrates. Formation of nanocluster is provided by condensation of cluster vapor on silicon in shock-compressed plasma layer. Results of studies show great potential of CPF application for the development of novel nanostructured metal-silicide materials for magnetic, thermoelectric and photovoltaic applications.

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