Grain size and doping effect on structure and electromechanical properties of polycrystalline silicon for MEMS applications

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Abstract. Grain size effect on microhardness and Young modulus of polysilicon layers was obtained by nanoindentation experiments: 14.1-16.3 GPa and 240-300 GPa, respectively, for the particle-diameter of 117-430 nm. The range of grain size correlated to mechanical properties exceed theoretical values was defined. The doping effect was considered. The grain size range of PECVD polysilicon with aspects of hardening and suitable conductivity is presented with the objective to formation of micro- and nanomechanical devices.

1. Introduction

Polycrystalline silicon has been widely used in metal-oxide-semiconductor field-effect-transistor, complementary metal–oxide–semiconductor, very-large-scale integration and solar cell processing technologies [1-3]. Doped polysilicon films are also of a great interest for the production of electrostatically movable mechanical elements of micro- and nanoelectromechanical systems (e.g. accelerometers, gyroscopes or pressure sensors) by surface as well as bulk micromachining [1-2,4]. Young's modulus, microhardness, conductivity and mobility of charge carriers are important characteristics of the material. The mechanical properties like Young's modulus and microhardness of these films have a strong impact on the design as well as on the reliability and functionality of these components [5]. Preferably, the material of moving elements should have higher values of the parameters. The questions about possibility to control of electromechanical parameters and monitoring their changes through doping during deposition are important as well as for two steps (deposition and subsequent ex-situ doping) process flow of the films fabrication. Moreover, the concentration of charge carriers of the films should be more 10^{19} cm^{-3} [6].

Intrinsic and doped films and layers of polysilicon mainly formed by low pressure and plasma-enhanced chemical vapor deposition (PECVD) or solid-phase crystallization of amorphous silicon [1,7]. It is known that PECVD allows to precision control properties of deposited films. Its properties are differ from ones formed by other chemical vapor deposition techniques. Growth rate and film uniform were higher for intrinsic films compare with using of doping gases [1,2,7].

The goal of the research is to establish the influence of grain size and ex-situ doping on the mechanical and electrophysical parameters of the plasma-deposited polysilicon films.

2. Experimental details

The plasma-enhanced chemical vapour deposition system was used for deposition of polycrystalline silicon films (PlasmaLab 100). Plasma-deposited polysilicon films, formed from silane and argon [8] were doped using the liquid PCl_3 diffusant (SD.OM-3M). The prediffusion and drive-in steps temperatures were 850ºC and 1150ºC, respectively. Concentration, mobility of charge carriers and resistivity after doping were measured using Hall/van-der-Pauw and contactless methods (Ecopia HMS-3000/1T and LEI 1510M40). The surface morphology and the mechanical properties were observed with an atomic force microscopy (NTEGRA Vita Probe Nanolaboratory). The mechanical properties like Young's modulus and microhardness were observed by nanoindentation method with used a diamond three sided Berkovich pyramid with an apex angle of θ = 70° as the indenter. Scratch force was 700-900 μN. The probe was indented into the sample surface at a constant speed; the process was accompanied by recording the values of the load and the appropriate depth of indenter penetration in the material, on the basis of which the resulting dependence (load curve) was plotted.

3. Results and discussion

The uniform polycrystalline silicon films in the thickness range from 0.2 to 2 μm were fabricated. The influence of parameters deposition films on their morphology was investigated early [8].

The experimental research of surface morphology and electro-physical properties of polycrystalline silicon films before and after doping are shown in Figure 1 and listed at Table 1. AFM-images show an increase of grain size. Concentration, mobility of charge carriers and resistivity values were amounted of $2\text{-}5\cdot10^{20}$ cm^{-3}, 12-35 $cm^2/(V\cdot s)$ and $8.6\text{-}9.4\cdot10^{-4}$ Ω·cm.

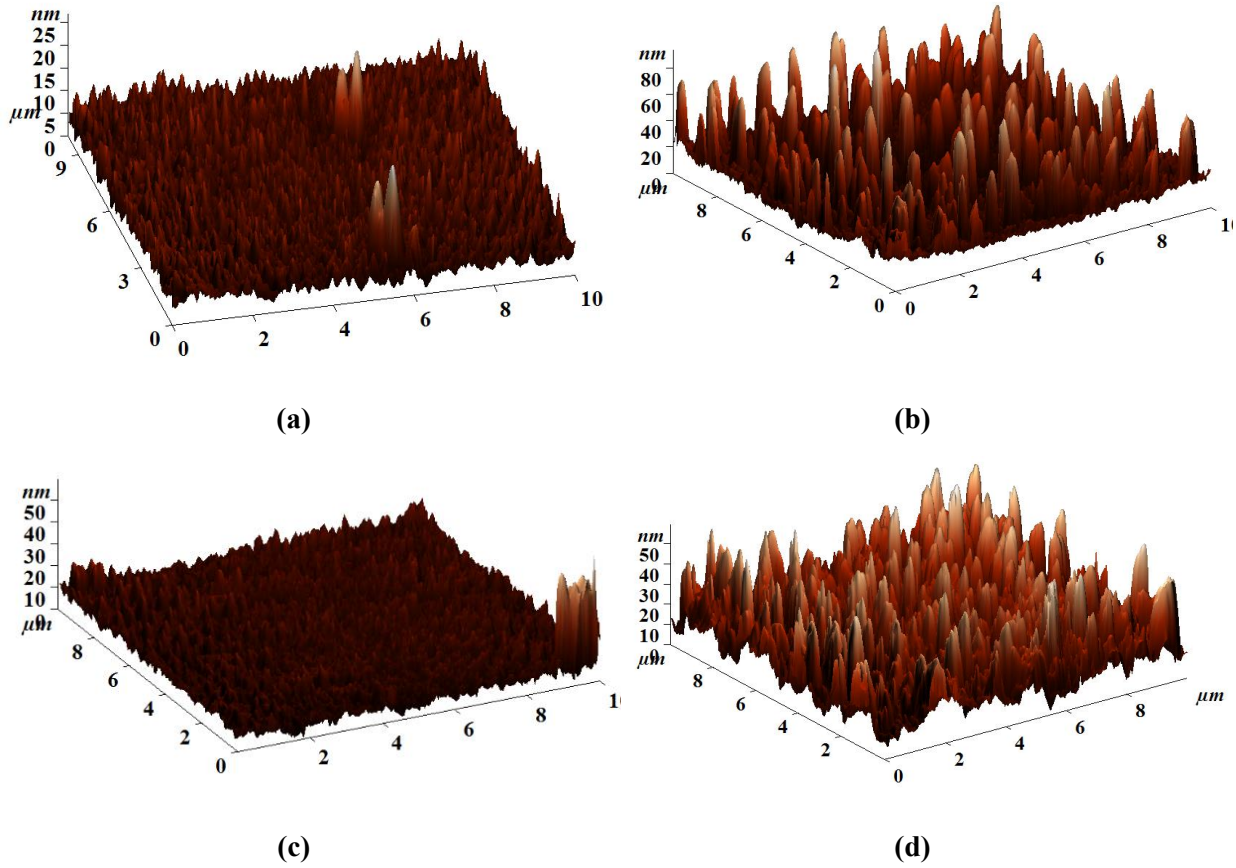


Figure 1(a-d). AFM images of the polycrystalline silicon films before **(a,c)** and after **(b,d)** doping

Root-mean-square (RMS) roughness increases from 2.1 nm and 2.6 nm to 12.1 and 8.9 nm for film thickness of 0.2 μm and 2.0 μm through doping. The average value of the grain size increases from 117 nm to 431 nm for the doped films. According to the well-known Hall-Petch dependence it should effect on microhardness and Young's modulus. However, there is a slightly change for the films with the referred grain size range. It should be mentioned that experimental values defined by nanoindentation are exceed theoretical values for Young's modulus [1,2,9]. It could be concerned with nanoindentation technique, plasma effect, and incorporation of chemicals during deposition, as well as conditions of bottom layer surface.

Table 1. Mechnical and electro-physical properties of the as-deposed and ex-situ doped polysilicon

#	Microhardness, GPa		Young modulus, GPa		Concentration, cm^{-3}, $\times 10^{20}$	Mobility, $cm^2/(V\ s)$	Resistivity, Ω/cm, $\times 10^{-3}$
	undoped	doped	undoped	doped			
17	7.7	23.6	249.5	284.9	3.191	18.78	1.042
18	10.4	18.3	302.3	310.1	3.484	18.55	0.965
19	14.8	13.7	242.7	278.2	5.842	11.35	0.942
20	18.8	21.5	293.2	224.3	7.824	16.53	4.862
21	17.4	18.4	380.4	242.3	1.861	26.42	1.270
22	18.4	17.2	247.1	286.1	3.874	30.69	0.525
23	14.1	16.3	299.3	271.2	2.015	35.98	0.861
24	16.4	18.4	282.9	242.7	2.491	27.74	0.903

It is assumed that, the most suitable polysilicon films for micro- and nanomechanical applications with aspects of high mechanical hardness and elasticity and acceptable conductivity are the films with the grain size within the range 117-430 nm, and the values of electromechanical parameters amounted to: 13-17 GPa, 240-300 GPa, $8.6\text{-}9.4\cdot 10^{-4}$ Ω/cm, 12-35 $cm^2/(V\cdot s)$. Such films (Figure 2) have been used for fabrication of micro- and nanomechanical gyroscopes and accelerometers (project number 14.575.21.0045) [10,11].

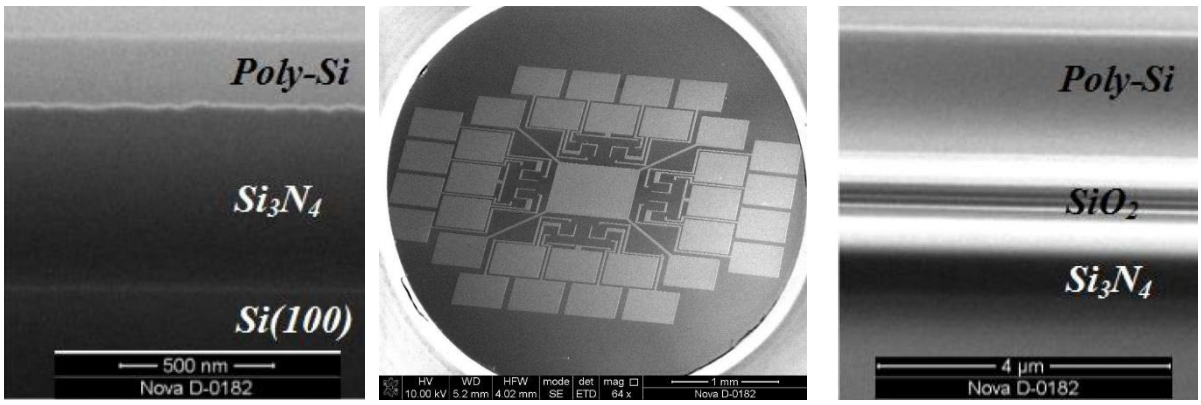
4. Conclusion

Polycrystalline silicon films were deposited by plasma-enhanced chemical vapour deposition. Doping effect on surface morphology was obtained. Root-mean-square roughness increases from 2.1 nm to 12.1 nm for 0.2 μm films thickness and from 2.6 nm to and 8.9 nm for 2.0 μm films. The average value of the grain size increases from 117 nm to 431 nm.

The correlation data of the grain size and root-mean-square roughness to micromechanical properties were presented. According to nanoindentations the microhardness and Young module of doped films were 13.7–23.6 GPa and 224.3–380.4 GPa, respectively. The mechanical parameters of the fabricated films were close to theoretical values or exceed it. Doping effect on mechanical properties was ambiguously and its average values were about ± 15%.

Concentration, mobility of charge carriers and resistivity of doped polysilicon films were $(2.0\text{–}7.8)\cdot 10^{20}$ cm^{-3}, 11.35–36.0 $cm^2/(V\cdot s)$ and $(0.525\text{–}4.87)\cdot 10^{-3}$ Ω·cm, respectively.

These films were found to be suitable and have been used in fabrication of micro- and nanomechanical gyroscopes and accelerometers (project 14.575.21.0045) to form two conducted layers: 1st bottom layer and 2nd layer of moveable inertial masses.



(a) **(b)**

Figure 2(a,b). SEM images of the bottom **(a)** and top **(b)** polycrystalline silicon layers of the micromechanical accelerometer

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