Etching of Polycrystalline Silicon in SF_6 Containing Plasmas

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Abstract

Reactive ion etching of polycrystalline and monocrystalline silicon in RF parallel plate system using SF_6/Ar and SF_6/O_2/Ar plasmas has been studied. In this work, we utilized samples of polysilicon deposited by a CVD process using two different technologies. Etch rates of polysilicon were analyzed as a function of various experimental parameters such as the reactive gas mixture and the implantation dose. A correlation between the etch rate and the mean size of polysilicon grains was observed .

1. Introduction

Deposition and etching of polycrystalline silicon are important steps of CMOS technology where polysilicon is used as a gate material. Plasmas containing fluorine (for example, SF_6) are widely used for silicon etching [1-3]. Most of studies concerning silicon etching by SF_6 were performed for monocrystalline silicon. However, etching characteristics of polysilicon may differ significantly from those of monosilicon [4-9]. In particular, one can expect that structural properties of polysilicon (grain size, porosity, surface roughness) have a considerable effect on etching. Furthermore, the influence of doping on etching characteristics can be more pronounced for polysilicon [10,11], as in this case the doping material is believed to be more concentrated at grain surfaces. In this work, a study was performed to compare etching characteristics of monosilicon and polysilicon in SF_6/Ar and SF_6/O_2/Ar plasmas. In the study, we used samples of polysilicon deposited by a CVD process using two slightly different technologies, one of them (LSI-USP) is well established, and the other has been recently developed in CCS-UNICAMP and now is under optimization.

2. Experiment

In etching experiments, a conventional capacitively coupled RF-driven (13.56 MHz) plasma reactor was used. RF power was applied to a smaller Al electrode (12 cm diameter). Experiments were performed with samples of polysilicon obtained by CVD process in two different versions: A (USP) and B (UNICAMP).

A: A 0.5 μm thick layer of polysilicon was deposited over a 0.2 μm thick layer of thermal silicon dioxide, which in turn, was deposited over a monosilicon substrate. Sample was patterned by a AZ5214 photoresist mask.

B: 1.0 to 2.5 μm thick layers of polysilicon were deposited over a 0.6 μm thick layers of thermal silicon dioxide, which in turn, were deposited over a monosilicon substrate. Samples were patterned by a AZ3012 photoresist mask.

Mixtures of gases containing SF_6, O_2 and Ar in different compositions were used for etching. Most of experiments were carried out at a gas pressure of 50 mTorr, total gas flows of 15-50 sccm, RF power of 20-50 W, DC self-bias voltage (built-up between the plasma and the smaller electrode) of 20 - 450 V. Etching time varied from 2 to 5 minutes. For the plasma diagnostic, optical emission spectroscopy (actinometry technique) was used which allowed us to monitor the density of fluorine radicals in the plasma. Etch depths were measured by a DEKTAK profiler, and to analyze the depth distribution of implanted dopants in polysilicon, a SIMS instrument was used. Accuracy of etch rate measurements was better than ±10%.

3. Results and Discussion

A. Experiments with polysilicon from LSI-EPUSP and monosilicon.

The results of silicon etch rate measurements in SF_6/Ar plasmas obtained at a fixed RF power of 20 W, pressure of 50 mTorr and varying SF_6/Ar ratio are shown in Table 1. Note that increase of SF_6 content resulted also in lowering of a self-bias.

Gas mixture SF_6/Ar (sccm)	DC bias (V)	poly-Si etch rate (nm/min)	*n* mono-Si etch rate (nm/min)	Ratio of etch rates: poly-Si / mono-Si
5/40	142	63	57	1.10
7.5/37.5	132	66	59	1.12
10/35	101	78	69	1.13
15/30	61	100	76	1.31
20/25	45	96	82	1.17
30/15	37	135	105	1.28

Table 1: Mono-Si and poly-Si etch rates in SF_6/Ar plasma, 50 mTorr, 20 W

The results show a tendency of increasing difference between polysilicon and monosilicon etch rates with growing SF_6 flow and decreasing DC self-bias, while the RF power is kept constant at a low level of 20 W. The ratio of etch rates ($ER_{poly-Si}$ / $ER_{mono-Si}$) grows from 1.10 at the lowest SF_6 content (SF_6/Ar =5/40 sccm, DC=142 V) to about 1.30 for the highest SF_6 content (SF_6/Ar =30/15 sccm, DC bias =37 V). The 20 % increase of etch rates definitely exceeds the inaccuracy of etch rates measurements (10%). These facts indicate that the difference between polycrystalline and monocrystalline silicon is mainly due to their different sensitivity to chemical/ion-induced mechanisms of etching. Because of porosity and higher surface roughness, polysilicon might have higher adsorption of fluorine atoms, and therefore, higher rate of spontaneous etching. For monosilicon, ion bombardment is more important as it helps to amorphyze surface layers and thus intensifies fluorine adsorption.

For higher RF powers (i.e., higher ion fluxes and DC bias values), the difference between the two cases tends to vanish, as seen from Table 2. From the data available in the literature [10], it follows that the concentration of dopant in silicon needs to be greater than $\cong 10^{19}$ cm^{-3}, for doping dependence of the etch rates to be observable. For the samples of monosilicon used in our experiments (both n- and p-type), the dopant concentration was in the order of 10^{15} cm^{-3}, so that no effect of doping could be expected for this case.

Furthermore, with addition of oxygen to SF_6/Ar mixtures, in some cases etch rates may become even slightly smaller for polysilicon than for monosilicon. This is likely due to oxidation of a silicon surface which is enhanced for more porous polysilicon. Note that both mono- and poly-Si etch rates reduce considerably with O_2 addition, and the effect of RF power (DC bias) on the etch rates is pronounced much stronger for the plasmas with oxygen than for the oxygen-free plasmas.

Gas mixture (sccm)	RF power (W)	DC bias (V)	poly-Si	mono- Si *n* type	mono-Si *p* type
SF_6/Ar 5/10	30	180	84	80	82
	50	300	109	99	105
	80	455	130	127	127
SF_6/Ar 15/30	30	107	103	97	97
	50	254	142	142	144
	80	390	186	186	175
SF_6/O_2/Ar 15/5/20	50	190	39	40	41
SF_6/O_2/Ar 10/10/20	30	125	20	19	20
	50	295	97	98	105
	80	455	135	131	140
SF_6/O_2/Ar 10/20/15	50	280	27	30	30

Table 2: Etch rates (in nm /min) in SF_6/Ar and SF_6/O_2/Ar plasmas, 50 mTorr

Actinometry data have confirmed (as it is known from another studies [9,12]) that the oxygen addition increases considerably fluorine content in the plasma. So the formation of a surface oxide due to presence of oxygen in the plasma has stronger effect then the rise of fluorine radicals flux to the surface, and this effect is more pronounced for polysilicon.

Some samples of polycrystalline silicon were implanted with relatively high doses of As and P and after that were thermally annealed. SIMS analyses were made that showed an uniform distribution of dopants within a polysilicon layer (0.5 μm thick) samples after annealing, without significant diffusion into a monosilicon substrate through an oxide layer. Polysilicon etch properties will depend on doping type, dose and the plasma conditions. The samples were etched using SF_6/Ar and SF_6/O_2/Ar plasmas. The results are shown in Table 3.

For SF_6/Ar plasmas, etch rates tend to reduce considerably with the dose (both for As and P dopants), with the reduction being as high as 50% for the highest doses used ($6x10^{20}cm^{-3}$). In the literature (for example, [10], [11]), an opposite trend was usually observed for etching of n-doped polysilicon, but as argued in [11], the conditions of annealing (performed after implantation) might be more important than doping itself, affecting strongly the etching results.

For plasmas with O_2 addition, the trend is not so clear, in most cases the etch rates do not change significantly as compared with not implanted samples. This gives further evidence that oxidation changes dramatically etching conditions at a surface of polysilicon.

Gas mixture (sccm)	DC bias (V)	poly-Si not implanted	poly-Si, implanted by dose (cm^{-3})			
			As, 10^{20}	As, $6x10^{20}$	P, $2x10^{20}$	P, $6x10^{20}$
SF_6/Ar 5/10	236	111	82	56	65	79
15/30	207	126	99	88	87	62
SF_6/O_2/Ar 15/5/20	200	96	97	96	76	103
10/10/20	245	60	64	31	55	52
10/20/15	241	39	35	29	23	32

Table 3: Etch rates (nm/min) of poly-Si, SF_6/Ar and SF_6/O_2/Ar plasmas, 50 W, 50 mTorr

B. Experiments with polysilicon from CCS-UNICAMP.

Results presented above show that etching in SF_6 containing plasmas is sensitive to structural properties (porosity) of polycrystalline silicon, under conditions where chemical etching by fluorine radicals is dominant. Here, we used etching in SF_6/Ar plasma to characterize properties of polysilicon samples deposited by a CVD technique from SiH_4/H_2 mixtures at high pressures (1.5 to 100 Torr) with substrate temperatures varying from 710 to 1000 ^oC (for more details, see elsewhere [13]). The results are presented in Table 4. Two different plasma processes were used. Note that for the process (a) the plasma conditions were chosen to provide a very low DC bias so that the etching is purely chemical, i.e. extremely sensitive to the porosity of the poly-Si. The process (b) is characterized by a higher DC bias, and thus by a higher contribution of an ion-induced mechanism to the etch rate. For comparison, etch rate for the sample from LSI-EPUSP is also shown. After polysilicon deposition, all samples were implanted with As or P. Note that thickness of polysilicon films varied from 1.0 to 2.5 μm, so that the specific volume doses were in the range of 0.5 – $1.0x10^{20}$ cm^{-3}. Thus relatively weak effect (20-30% at most) of implanting on the etch rate can be expected.

As seen from the Table 4, the etch rates vary considerably between the samples studied in the range of 100 to 300 nm/min for the process (a), at a low DC bias. At the same time, the etch rates vary only slightly, in the range of 120 to 150 nm/min for the process (b), as can be expected due to reduced contribution of chemical etching at a higher DC bias. The lowest etch rate obtained is equal to that obtained for the sample from LSI-EPUSP (not implanted polysilicon). Certain correlation can be observed between the mean size of grains and the etch rates (see figure 1). The highest etch rates (and the largest grain sizes) correspond to the highest pressures and temperatures used for deposition. It is likely that the mean size of grains correlates with the porosity of the film. Therefore, etch rate results obtained under the conditions of predominantly chemical etching by fluorine can be used for characterization of the polysilicon film porosity. It is interesting to note that no evident correlation is observed between the surface roughness and the etch rate.

Samples	Pressure (Torr)	Temp (°C)	SiH_4 flow (sccm)	H_2 Flow (sccm)	Dopant surface dose (cm^{-2})	Mean size of grains (nm)	Mean roughness (nm)	(a) Etch rate (nm/min)	(b) Etch rate (nm/min)
CCS UNICAMP	100	1000	40	36100	P, 10^{16}	148.7	81.6	290	---
	100	900	40	36100	P, 10^{16}	73.6	16.0	304	147
	100	740	40	36100	P, 10^{16}	37.3	11.5	260	140
	100	900	40	22500	P, 10^{16}	66.3	---	270	---
	5.0	850	40	4800	As, 10^{16}	49.3	88.1	198	125
	5.0	800	40	4800	As, 10^{16}	23.9	42.7	201	125
	2.5	770	60	0	As, 10^{16}	35.5	5.9	220	120
	1.5	770	60	0	As, 10^{16}	13.8	58.5	140	---
	1.5	710	60	0	As, 10^{16}	30.2	4.0	105	---
LSI- EPUSP	---	---	---	---	Not implanted	---	---	97	---

Table 4: Deposition conditions and etch results for poly-Si (CCS-UNICAMP), (a) plasma SF_6/Ar= 30/15 sccm, power RF 20 W, pressure 50 mTorr, DC self-bias 23 V, (b) plasma SF_6/Ar=20/10 sccm, power RF 50 W, pressure 50 mTorr, DC self-bias 128 V.

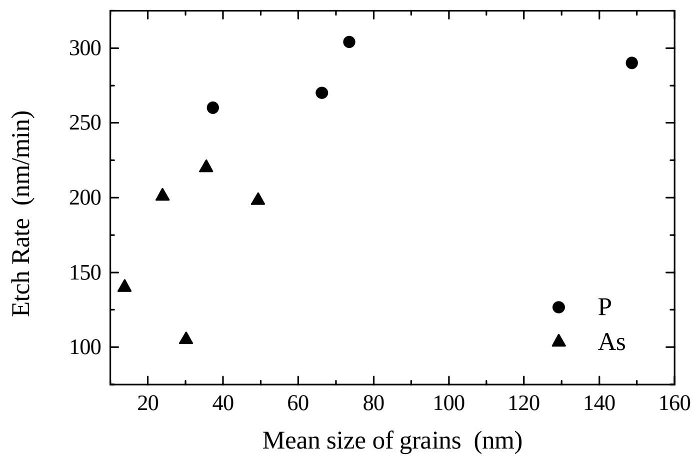

Figure 1: Etch rate as a function of mean size of grains of doped poly-Si in SF_6/Ar plasma. Process (a): $30SF_6/15Ar$, 20 W, 50 mTorr.

4. Conclusions

Results of the study of mono- and polycrystalline silicon etching in plasmas containing SF_6 are presented. It is shown that, under the conditions of predominantly chemical etching (low self-bias, high SF_6 content in the plasma), etch rate depends on structural properties of the silicon, so that it can be used for characterization of polysilicon porosity. Strong correlation between the mean size of grains in polysilicon and the etch rate in a SF_6/Ar plasma is demonstrated. It is shown that doping of polysilicon by As and P at dose levels exceeding 10^{20} cm^{-3} leads to a significant reduction of etch rates. Mechanisms responsible for this reduction are not clear yet, and further studies of the effect are planned.

Addition of oxygen to a SF_6/Ar plasma has a strong effect on polysilicon etching due to surface oxidation and the corresponding drop of the etch rate. The effect seems to be more pronounced for polysilicon that for monosilicon.

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