Resist characteristics simulation of HSQ electron beam resist

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Hydrogen Silsesquioxane (HSQ) is used as a high-resolution resist with resolution down below 10 nm half-pitch. High-contrast and high-resolution patterning in the negative electron beam HSQ resist has numerous potential applications. Our aim in this work was to investigate lithographic parameters in thicker resist films because the resist thickness of 150 nm is not sufficient for repeatable reactive ion etching (RIE) of various thin films for many applications. The main focus was on investigation of the line-width dependence on the exposure dose in thick HSQ resist and simulation of resist profiles.

Симулация на характеристиките на електроннолъчевия резист HSQ (А. Бенкурова, К. Вутова, Е. Колева, И. Костич, А. Ритомски, Г. Младенов). *Негативният резист HSQ се използва като резист с висока резолюция под 10 нанометра половин терен. Висок контраст и висока разделителна способност моделиране в HSQ има множество потенциални приложения. Нашата цел в тази работа е да се изследва литографски параметри в дебел устои филми защото устои дебелина от 150 nM, не е достатъчно за повторяеми реактивно йонно ецване (РИО) на различни тънки филми за много приложения. Основният акцент е върху разследване на линия ширина зависимостта относно дозата на експозиция в гъста HSQ устои и симулация на устои профили.*

Introduction

Hydrogen Silsesquioxane (HSQ) is used as a high-resolution resist with resolution down below 10 nm half-pitch [1]. On the other hand, as inorganic resist material, it is interesting as masking layer in reactive ion etching (RIE). It is inorganic compounds with the chemical formula $[HSiO_{3/2}]_{2n}$ (Fig. 1) [2]. Silicon atoms sit at the corners of a cubic structure. Each silicon atom is bonded to a hydrogen atom and bridges 3 oxygen atoms.

The use of HSQ as a negative tone resist for electron beam lithography (EBL) was published in [3]. They suggested that the silicon hydrogen bonds (which are weaker than SiO bonds) are broken during e-beam irradiation and converted to silanol (Si–OH) groups in the presence of absorbed moisture in the film. These silanol groups are unstable and condense to break the caged molecule to form a linear network.

Investigation of lithographic characteristics of HSQ resist were published in numerous publications [4]. When small features are desired, the ultimate resolution is set by various factors such as beam size, resist material, exposure dose, development process and also the writing strategy [5].

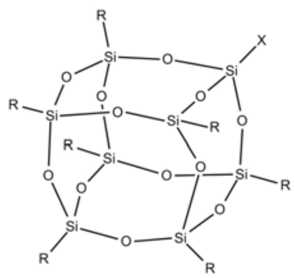


Fig. 1 Hydrogen Silsesquioxane (HSQ) molecule [2].

Sub-10-nm lines in HSQ have been successfully achieved when using very small spot sizes and acceleration voltages of 100 keV [6, 7].

High-contrast and high-resolution patterning in HSQ has numerous potential applications. For instance, quantum dots, large-area patterning of dot structures for the fabrication of high-density bitpatterned media, novel superconducting single-photon detectors [8, 9].

Patterning of submicrometer structures in III/V semiconductors using 150 nm thin HSQ as an etch mask in $SiCl_4$ plasma was published in [10]. TiO_2 structures for gas detection sensors with a minimal size of 70 nm were successfully fabricated by ICP RIE etching in CF_4/Ar plasma through 120 nm thin negative e-beam resist HSQ [11].

Usually the thickness of HSQ masking layer varies in the 10-150 nm range. Our aim in this work was to investigate lithographic parameters in thicker resist films because the resist thickness of 150 nm is not sufficient for repeatable reactive ion etching (RIE) of various thin films for many applications. The main focus was on investigation of the line-width dependence on the exposure dose in thick HSQ resist and simulation of resist profiles. The resist thicknesses were chosen 800 nm and 1200 nm on the base of HSQ selectivity for etching of various thin films with thickness of hundreds nanometers. Negative resist HSQ FOX-25 (*Dow Corning*) was appropriate for our investigation.

Experimental investigation

Experimental data needed for simulation were acquired from line tests. Long single lines were exposed at various exposure doses using electron beam with Gaussian electron energy distribution. The substrate was broken after development perpendicularly to lines for getting line profiles in the investigated negative-tone resist. Afterwards, the width of the obtained resist profile was measured at various depths along the resist thickness including levels of measurements at the top and at the bottom of the resist (Fig.2).

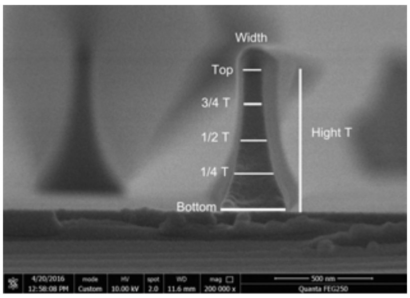


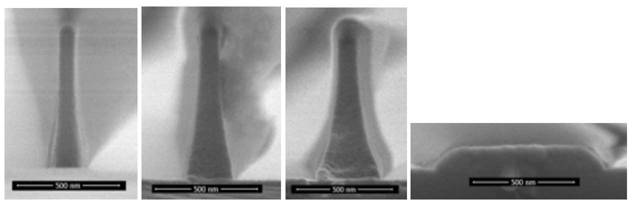
Fig.2. Measurement levels along the line height for the resist profiles in HSQ.

Negative resist HSQ FOX-25 (*Dow Corning*) was spin coated for 800 and 1200 nm thicknesses. After spinning, the HSQ layer was prebaked on a hotplate for 2 min at 150°C. Development process was done in tetra-methyl-ammonium hydroxide (TMAH) Microposit MF-322 developer (2.38 %) for 60 sec and rinse 10 sec in deionized water.

Experiments were performed using electron beam lithography system Elphy Quantum (*Raith*) installed on scanning electron microscope (SEM) Quanta FEG (*FEI*). The minimal spot and minimal possible beam current of 20 pA at electron energy of 30 keV have been adjusted. Line step size was 13.3 nm and line dwell time 0.0004 ms.

Resist profiles, obtained in 700 nm thick HSQ FOX-25 for various exposure line doses, are demonstrated in Fig.3. Measured line profile widths at the top/bottom levels of the resist thickness for a dose of 555 pC/cm were 74 nm/115 nm (Fig. 3a), 90 nm/233 nm for 690 pC/cm (Fig. 3b), and 98 nm/410 nm for 863 pC/cm (Fig. 3c). For comparison, a resist profile in 150 nm thin HSQ is shown in Fig. 3d.

To get an optimal high-aspect ratio resist profiles required for RIE, it is necessary to optimize exposure parameters. The width on the top is increasing slowly with the exposure dose, because the main contribution from forward electron scattering is expected. At the bottom of the resist profile, the width is influenced significantly by backscattered electrons.



a) b) c) d)

Fig.3. Comparison between resist profiles in 700 thick HSQ FOX-25 resist for various exposure line doses. The profile widths at the top/bottom levels of the resist thickness are: (a) 74 nm/115 nm for 555 pC/cm, (b) 90 nm/233 nm for 690 pC/cm, (c) 98 nm/410 nm for 863 pC/cm; (d) in 150 nm thin HSQ - 635 nm/857 nm for 1021 pC/cm

Measured data for profiles' widths at 5 levels of measurements along the HSQ resist thicknesses (at the top, ¾, ½, ¼ of the thickness *T*, and at the bottom (resist/substrate interface) - Fig. 2) for exposure with different line doses is presented in Table 1 and Table 2 for 800 nm and 1200 nm HSQ over Si substrate, respectively.

Table 1

Data for line profiles' widths measured at the top of the resist, at ¾ T, at 1/2 T, at ¼ T and at the resist bottom for 800 nm HSQ exposed by different doses

Line Dose	Width	Width	Width	Width	Width	Line Height
pC/cm	nm	nm	nm	nm	nm	nm
	at top	at 3/4 T	at 1/2 T	at 1/4 T	at bottom	
	collapse					
505.56	66	70	80	90	80	735
530.23	69	74	81	97	92	735
542.56	70	75	82	99	106	735
554.89	74	78	84	106	115	736
567.22	75	80	86	112	126	736
616.54	83	85	96	130	167	738
690.53	90	93	110	160	233	740
739.85	92	96	123	180	272	743
801.50	97	104	137	205	339	747
924.81	100	118	160	265	470	760
986.47	102	123	170	286	550	775
1048.12	104	128	180	320	630	790
1109.77	105	135	193	350	730	803
1171.43	106	145	205	360	808	811

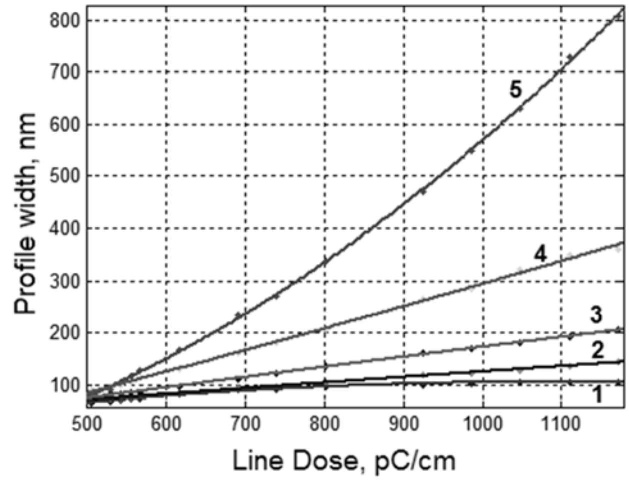
Table 2

Data for line profiles' widths measured at the top of the resist, at ¾ T, at 1/2 T, at ¼ T and at the resist bottom for 1200 nm HSQ exposed by different doses

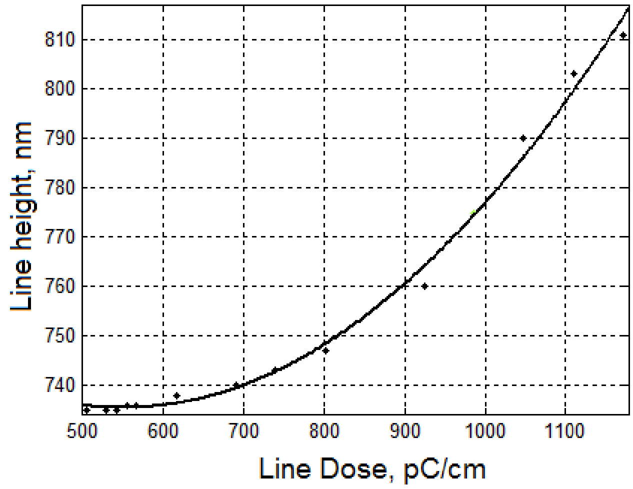
Line Dose	Width	Width	Width	Width	Width T	Line Height
pC/cm	nm	nm	nm	nm	nm	nm
	at top	at 3/4 T	at 1/2 T	at 1/4 T	at bottom	
664.66	70	92	230	1200	4200	1280
584.90	51	76	160	500	1400	1160
564.96	46	75	145	440	1070	1091
531.73	43	71	130	340	780	1070
498.50	39	64	117	275	540	1070
465.26	37	62	112	240	394	1040
432.03	36	61	107	205	291	1050
405.44	36	60	105	186	254	1058
392.15	collapse					

Optimization of exposure parameters

The optimization of the exposed HSQ profiles was done for 800 nm and 1200 nm HSQ resists separately. Models are estimated for the different profile widths: Y_1 - at the top of the resist, Y_2 – at ¾ T, Y_3 – at 1/2 T, Y_4 - at ¼ T and Y_5 – at the resist bottom as well as the line hight – H, depending on the exposure doses *d*.

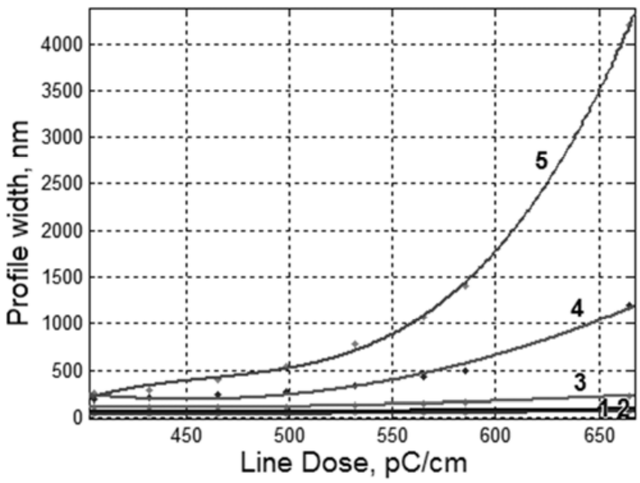


a) profile widths: 1 - at the top of the resist, 2 – at ¾ T, 3 – at 1/2 T, 4 - at ¼ T and 5 – at the resist bottom

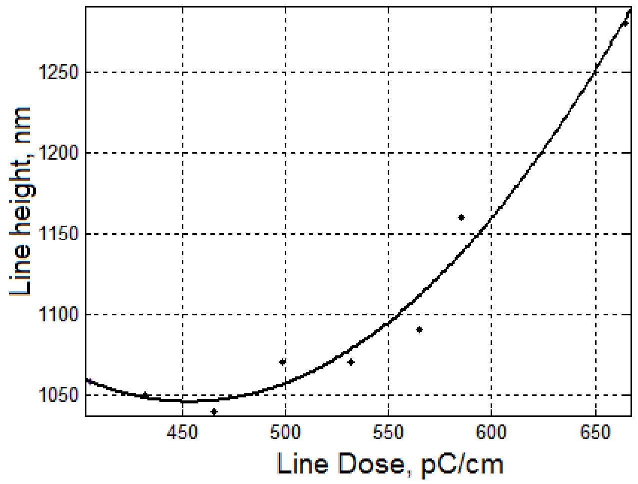


b) profile hights

Fig. 4. Experimental and estimated dimensions of 800 nm HSQ resist profiles (cross-sections)



a) profile widths: 1 - at the top of the resist, 2 – at ¾ T, 3 – at 1/2 T, 4 - at ¼ T and 5 – at the resist bottom



b) profile hights

Fig. 5. Experimental and estimated dimensions of 1200 nm HSQ resist profiles (cross-sections)

Table 3
Estimated models of the dimensions of HSQ resist profiles

800 nm HSQ	
Model	R^2, %
Y_1= - 0.0001156 d^2 + 0.2493 d - 29.47	98.81
Y_2= - 4.912*10^{-6} d^2 + 0.1149 d + 14.91	99.73
Y_3= - 1.134*10^{-5} d^2 + 0.2132 d - 29.32	99.81
Y_4= 3.309*10^{-5} d^2 + 0.37 d - 109.4	99.81
Y_5=0.0006232 d^2 + 0.05251 d - 105.8	99.97
H =0.0002044 d^2+ -0.2244 d + 797	99.36
1200 nm HSQ	
Model	R^2, %
Y_1= 0.0006103 d^2 -0.5237 d + 148.2	99.77
Y_2= 0.0003643 d^2 -0.2644 d + 106.9	98.97
Y_3=0.002189 d^2 -1.871 d + 506	99.84
Y_4= 0.0214 d^2 -19.29 d + 4536	98.30
Y_5=0.0003928 d^3 + -0.5432 d^2+ 252.7 d - 3.911*10^4	99.91
H =0.005313 d^2 -4.82 d + 2139	97.29

The obtained results are presented in Fig. 4 and Fig. 5 for 800 nm and for 1200 nm HSQ resists. There with points are presented the experimental data and curves correspond to the estimated models.

In Table 3 are presented the estimated models for the dependencies of the dimensions of HSQ resist profiles, together with the values of the corresponding multiple correlation coefficients R. These coefficients are tested for significance and their values are measures of the accuracy of the estimated models. The closer to 1 the value of R is, the better the model describes the variations of the quality characteristics as a function of the process parameters. All models have enough high and significant values of their multiple correlation coefficients and consequently the models are good for prediction and optimization of the considered quality characteristics.

It can be seen, that at smaller doses the difference between the 5 investigated dimensions are smaller, which corresponds to more close to parallel side walls of the exposed and developed lines. On the other hand, there the line heights are smaller. Compromise solutions should be found according the exactly required dimensions.

Conclusions

Investigation of lithographic parameters in thicker HSQ resist films is performed. The resist thickness of 150 nm is not sufficient for repeatable reactive ion etching (RIE) of various thin films for many applications. Models for the line-width dependence on the exposure dose in thick HSQ resist are estimated and simulation of resist profiles is done.

Acknowledgements

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