MuP07

Precise control of thickness distribution of Mo/Si multilayer coatings for EUV optics using a moving deposition shutter system

***M. Shiraishi, K. Akiyama, T. Komiya, T. Tomofuji,
N. Kandaka, T. Oshino, and K. Murakami***

Nikon
EUVL Development Department

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Outline

- Introduction
  - * “Moving deposition shutter (MDS)”
- Concept of distribution control
  - * “Inversed matrix method”
- Results of distribution control
- Summary

Introduction

EUV (extreme ultraviolet) optics uses multilayer-coated mirrors (e.g. Mo/Si) for EUV reflection.

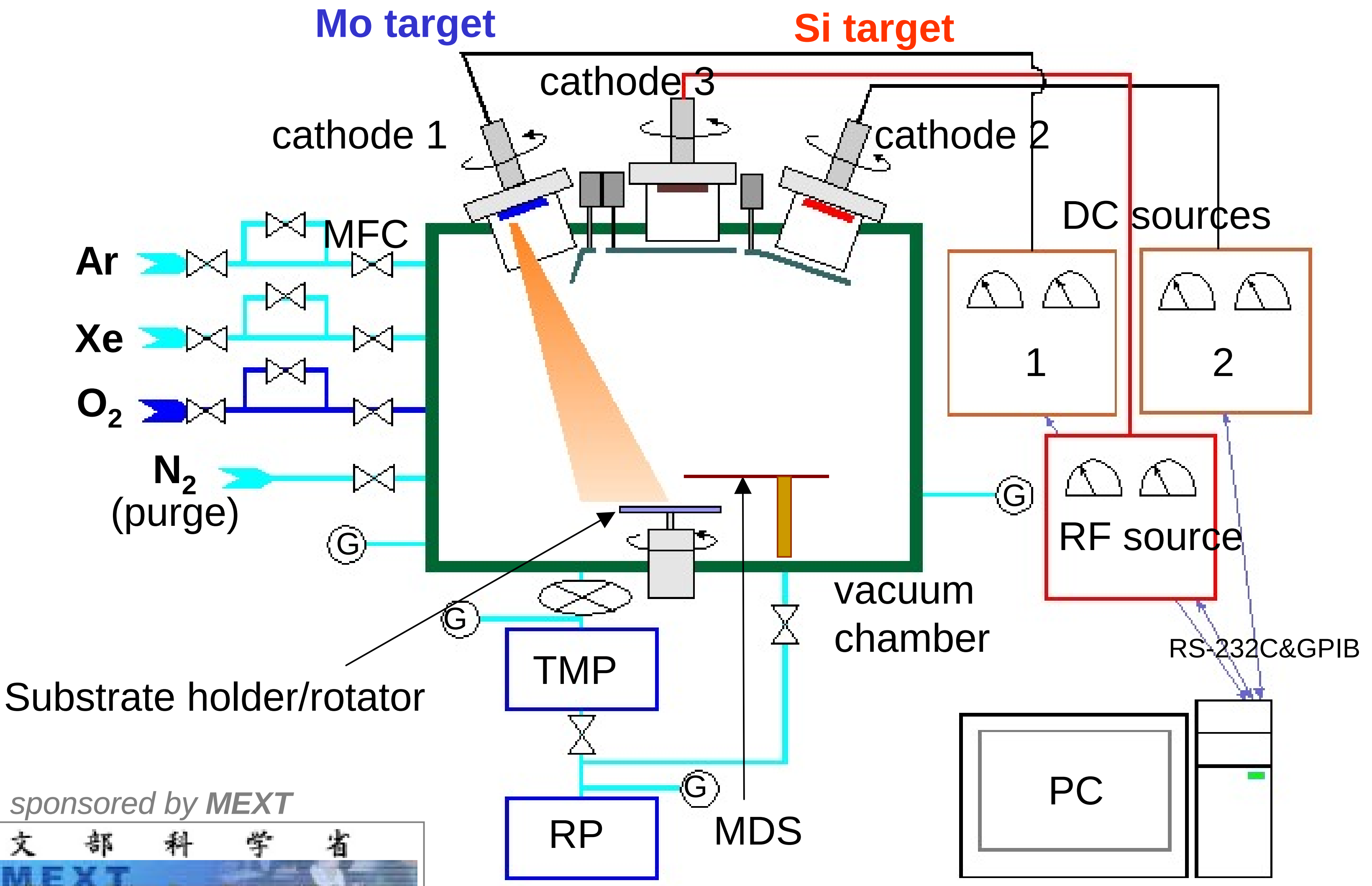
Since Mo/Si multilayers work as band-pass filters in both wavelength and angular domain in EUV region, the thickness of multilayers at each position on mirrors should be optimized according to the incidence angle at the position, in order to obtain sufficient reflectivity and other properties.

Hence, precise control and correction of thickness distribution of Mo/Si multilayer coatings is required.

We have developed experimental system of precise control and correction of thickness distribution of Mo/Si multilayers using a moving deposition shutter (MDS) attached to a rotary magnet cathode sputtering system.

Deposition system

Low-pressure rotary magnet cathode (RMC) sputtering



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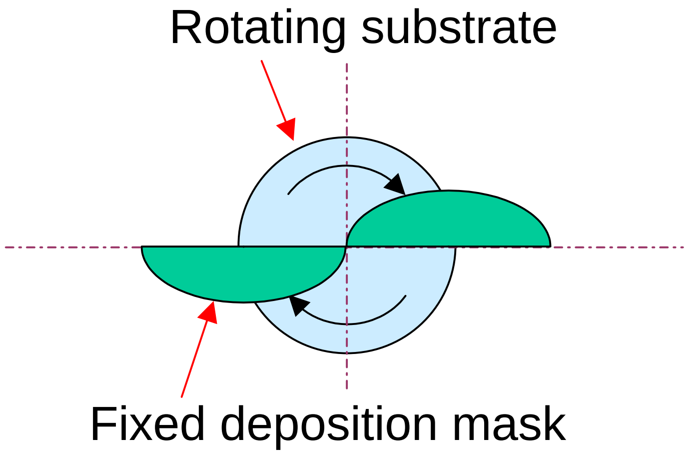
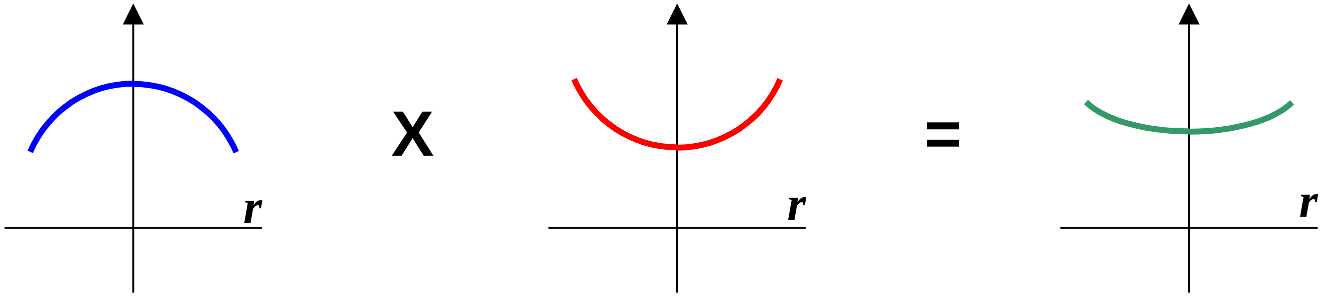
Conventional distribution control

Fixed deposition mask



A mask with designed aperture shape is placed (fixed) near a rotating substrate. The radial distribution of aperture angle (along circumference at *r*) determines the radial thickness distribution.

To refine distribution, re-fabrication of mask with new shape is needed.



intrinsic (no mask) thickness distribution (rotational average)

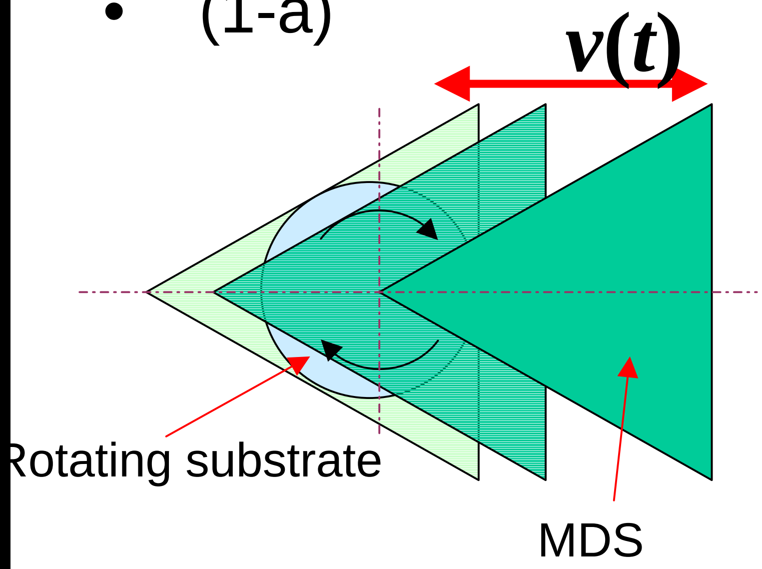
radial **correction** distribution of aperture angle of mask

desired thickness distribution

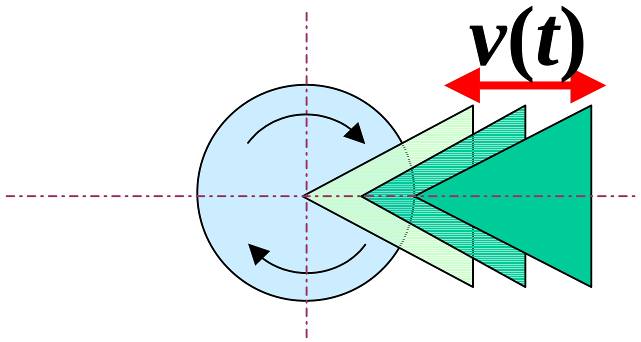
Moving deposition shutter

"Moving deposition shutter (MDS)" - Triangular type

- (1-a)



- (1-b)



MDS scans in one direction over the substrates with time-dependent velocity function $v(t)$.

(1-a) is adequate when the intrinsically-convex distribution is corrected to be uniform. ~ *Tohoku University type*

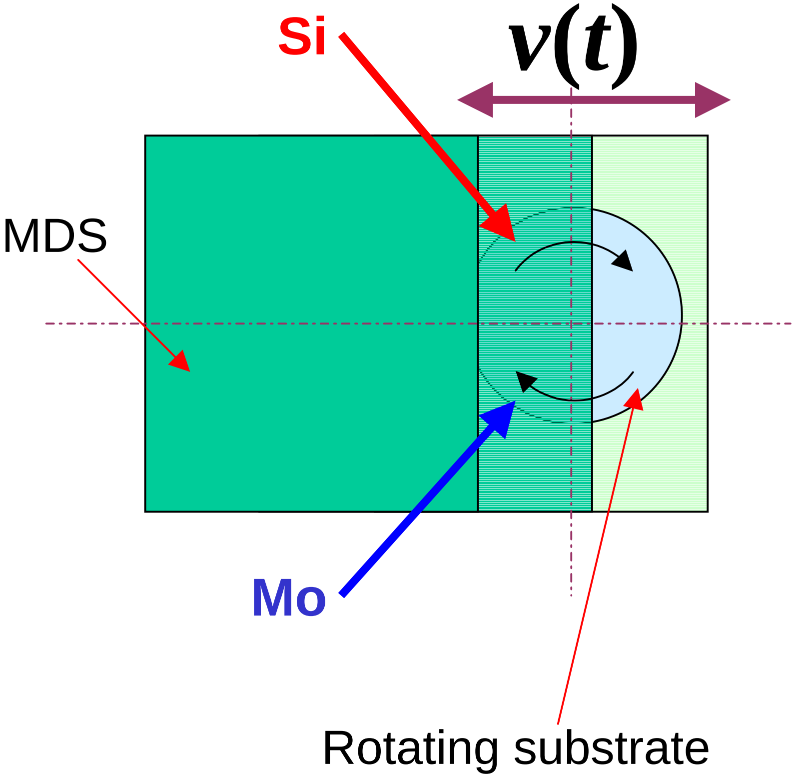
(1-b) is adequate when the intrinsically-concave distribution is corrected to be uniform.

To refine distribution, only re-calculation of the $v(t)$ is needed. No need of re-fabrication of the mask (shutter).

Moving deposition shutter

"Moving deposition shutter (MDS)" - Square (edge) type

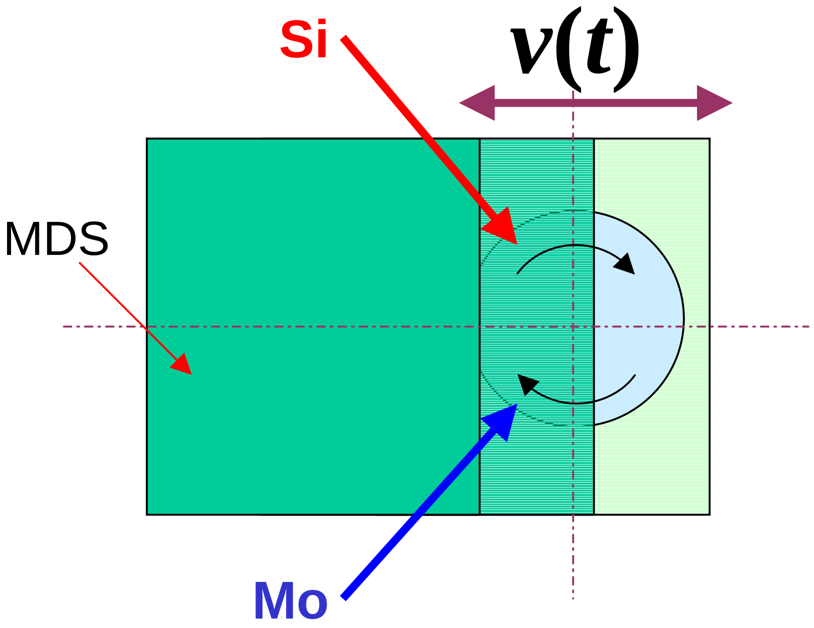
- (2)



MDS scans in one direction over the whole area of substrates from full open to full closed.

Using a square type MDS without cusp (instead of a triangular type), it is possible to improve the controllability of the distribution at the substrate center.

MDS basic concept



Thickness distribution of deposited films depends on the time-dependent velocity function

$v(t)$

of the MDS.

It is more difficult to solve $v(t)$ analytically in order to correct the thickness distribution than conventional method.

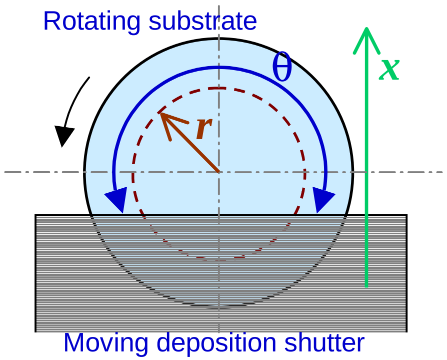
Inversed matrix method

Concept (theory)

Calculation of thickness of deposited films

$$d = s \times a \times t$$

thickness deposition **rate** **aperture** ratio deposition **time**



Extended calculation

Assumption: Rotation of substrate is sufficiently faster than the MDS scanning.

$$\vec{D}(r) = [\; P_{xr} \;] \times \vec{T}(x)$$

thickness distribution distribution matrix MDS **duration**

r : radius on substrates

x : MDS edge position

θ : angle

whereas

$$P_{xr} = \int_{\theta_1}^{\theta_2} S(r,\theta)\, d\theta$$

matrix element **rate** distribution integrate within **aperture**

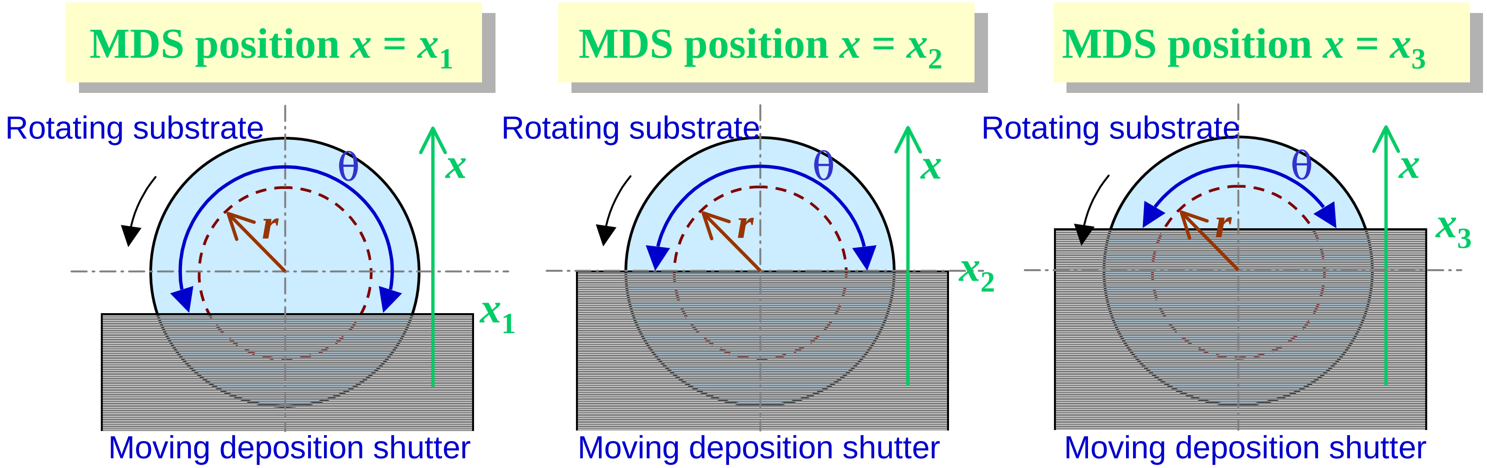
$$\theta_2 - \theta_1 = A(r,x) = \begin{cases} 2\pi - 2\arccos(u) & (x < 0), \\ 2\arccos(u) & (x \geqq 0) \end{cases} \qquad u = \begin{cases} |x|/r & (|x|/r \leqq 1), \\ 1 & (|x|/r > 1) \end{cases}$$

aperture angle

(square type)

Amount of deposition

Amount of deposition during one layer process at radius *r* (rotational average = sum along the arc of aperture at *r*)



MDS duration at *x*: $\Delta T(x_1)$ $\Delta T(x_2)$ $\Delta T(x_3)$

Aperture angle at radius *r*: $\theta = A(r, x_1)$ $\theta = A(r, x_2)$ $\theta = A(r, x_3)$

Amount of depo. during unit time: $P_1(r)=\int S(r, \theta)\, d\theta$ $P_2(r)=\int S(r, \theta)\, d\theta$ $P_3(r)=\int S(r, \theta)\, d\theta$

Amount of depo. during ΔT:

$$\underbrace{P_1(r)\Delta T(x_1) + P_2(r)\Delta T(x_2) + P_3(r)\Delta T(x_3) + \dots}$$

Total amount of deposition during 1 layer process

$$D(r) = \sum\left(P_n(r)\Delta T(x_n)\right)$$

...This is just a formula of a product of a matrix and a vector.

Velocity function

Formula for calculation of film thickness

$$\vec{D}(r) = [\; P_{xr} \;] \times \vec{T}(x)$$

thickness distribution — distribution matrix — MDS duration at *x*

Solve with inversed matrix

$$\vec{T}(x) = [\; P_{xr} \;]^{-1} \times \vec{D}(r)$$

duration due — inversed distribution matrix — target distribution

$$t = \int_{x_0}^{x} T(x)\,\mathrm{d}x = f(x)$$

time ***t*** at MDS position ***x*** (sum of duration)

$$x = f^{-1}(t)$$

MDS position ***x*** at time ***t***

Solution of velocity function

$$v(t) = \frac{\mathrm{d}x(t)}{\mathrm{d}t}$$

velocity function

Required information

$$\vec{D}(r) = \left[\; P_{xr} \;\right] \times \vec{T}(x)$$

target distribution
(given)

distribution matrix

MDS duration
(to be solved)

$$P_{xr} = \int_{\theta_1}^{\theta_2} S(r,\theta)\, d\theta$$

matrix element

rate distribution

within aperture angle

Determined by MDS shape

→ Simple geometric calculation

Determined by sputtering configuration, target materials and relative position between substrate and targets (cathodes)

This can be obtained from the 2D distribution of
a single layer deposited without substrate rotation.

*** Velocity function $v(t)$ can be solved**
from any target distribution D .

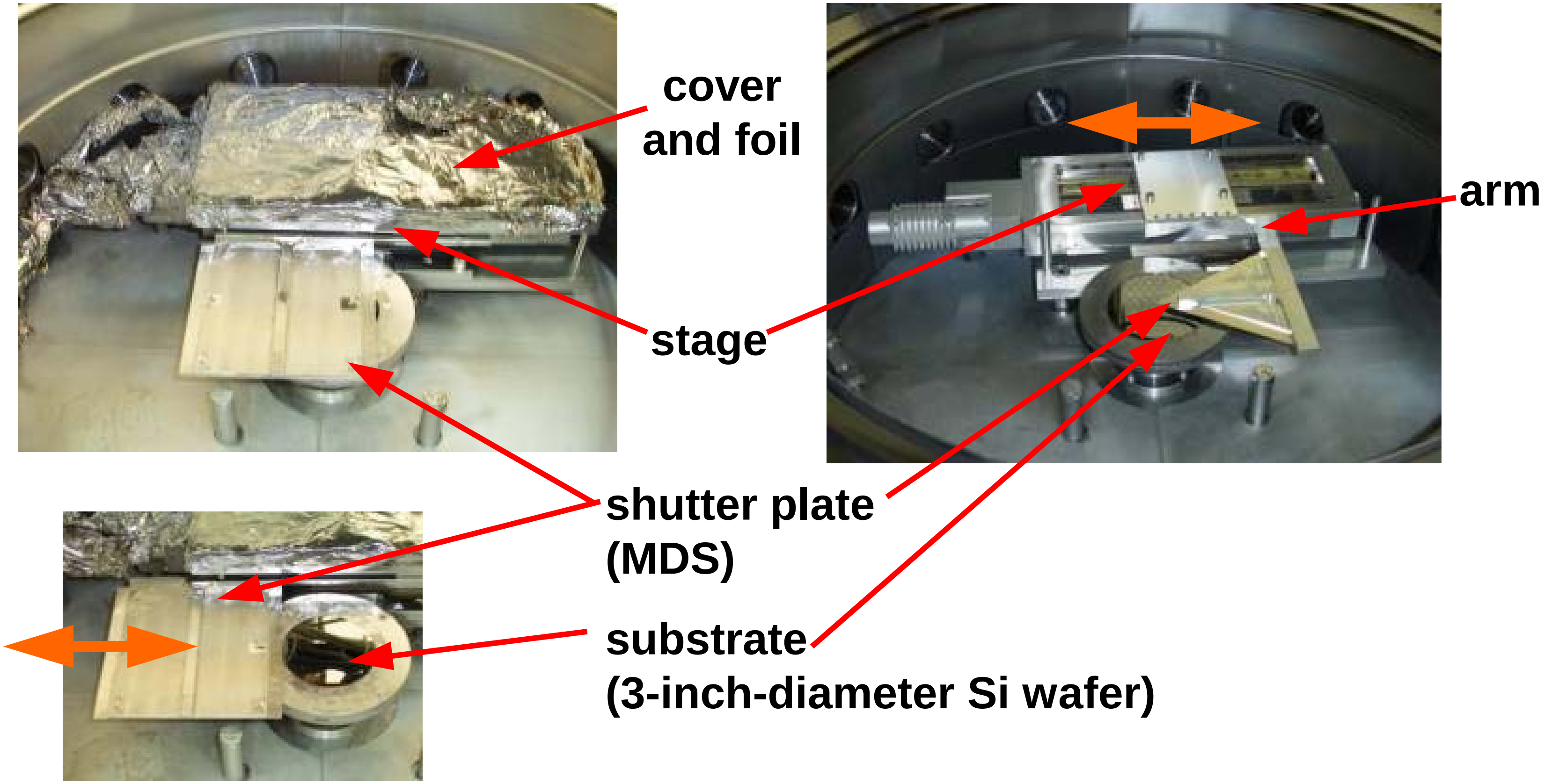
Experimental configuration

MDS and stages in an RMC sputtering system

MDS – square (edge) type

**** This experiment***

MDS – triangular type



cover and foil

arm

stage

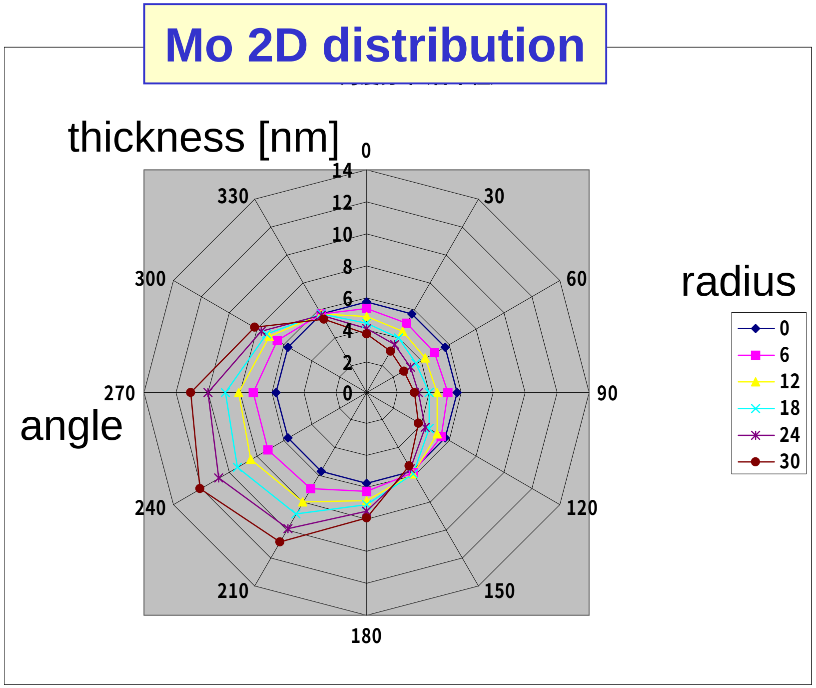
shutter plate (MDS)

substrate (3-inch-diameter Si wafer)

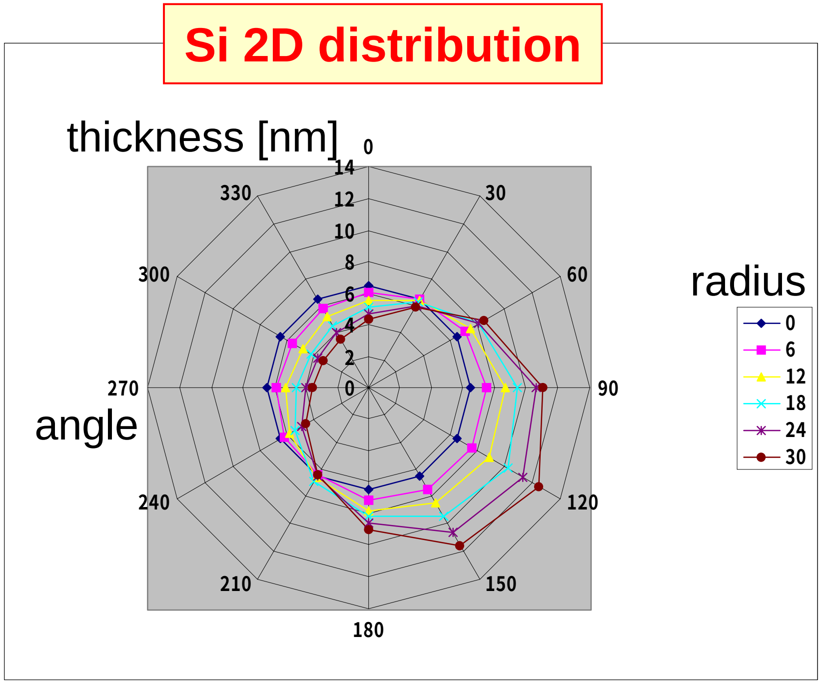
2D distribution

2D distribution on substrates of single layers of Mo and Si

(<u>without substrate rotation</u>)

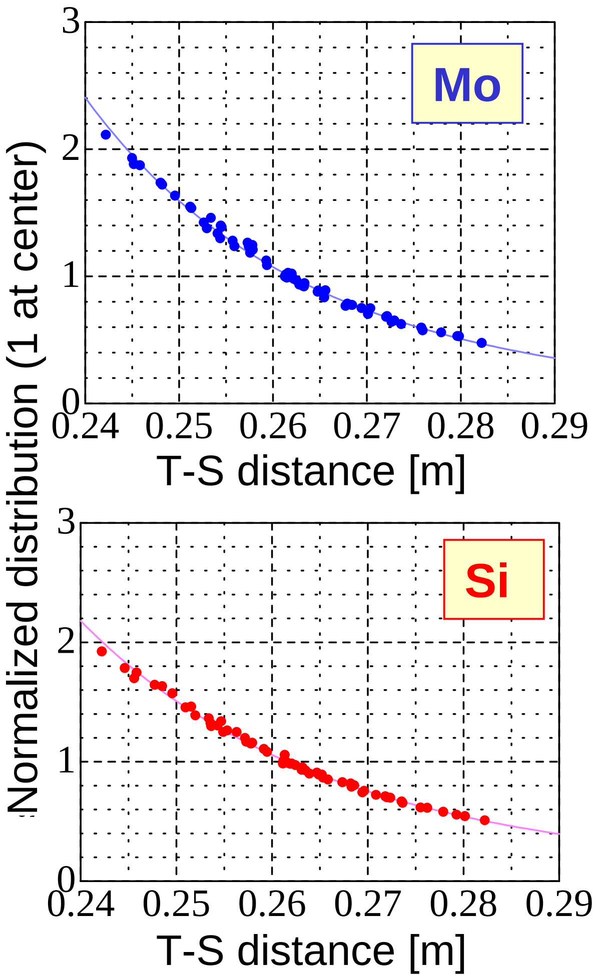


Mo 2D distribution



Si 2D distribution

2D distribution fitting



In this experiment,
the thickness distribution of Mo and Si seems to depend on only the distance between the measured point on the substrate and the center of the targets,
within the measured area (3-inch diameter)

Each distribution was fitted by a function of the T-S distance.
(Actually, distribution depends on also angles of ejection from targets and injection into substrates of sputtered atoms.)

Distribution matrix

Make a matrix whose elements are
“deposition rate at radius *r* when MDS is at position *x*”
using the fitted function from Mo 2D thickness data.

Mo

$$\left[\ P_{xr}\ \right]$$

Mo	1"	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
200	r/X	-30	-27	-24	-21	-18	-15	-12	-9	-6	-3	0	3	6	9	12	15	18	21	24	27
1	0.75	0.0293	0.0293	0.0293	0.0293	0.0293	0.0293	0.0293	0.0293	0.0293	0.0293	0.0145	0	0	0	0	0	0	0	0	0
2	2.25	0.0293	0.0293	0.0293	0.0293	0.0293	0.0293	0.0293	0.0293	0.0293	0.0293	0.0144	0	0	0	0	0	0	0	0	0
3	3.75	0.0293	0.0293	0.0293	0.0293	0.0293	0.0293	0.0293	0.0293	0.0293	0.0231	0.0142	0.0057	0	0	0	0	0	0	0	0
4	5.25	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0198	0.0141	0.0085	0	0	0	0	0	0	0	0
5	6.75	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0294	0.0246	0.0183	0.0139	0.0096	0.0041	0	0	0	0	0	0	0
6	8.25	0.0295	0.0295	0.0295	0.0295	0.0295	0.0295	0.0295	0.0295	0.0217	0.0174	0.0138	0.0103	0.0064	0	0	0	0	0	0	0
7	9.75	0.0296	0.0296	0.0296	0.0296	0.0296	0.0296	0.0296	0.0255	0.0201	0.0166	0.0137	0.0108	0.0077	0.0032	0	0	0	0	0	0
8	11.25	0.0297	0.0297	0.0297	0.0297	0.0297	0.0297	0.0297	0.023	0.0192	0.0162	0.0135	0.011	0.0083	0.0052	0	0	0	0	0	0
9	12.75	0.0299	0.0299	0.0299	0.0299	0.0299	0.0299	0.0262	0.0213	0.0184	0.0157	0.0134	0.0112	0.0088	0.0064	0.0027	0	0	0	0	0
10	14.25	0.03	0.03	0.03	0.03	0.03	0.03	0.0238	0.0204	0.0176	0.0155	0.0133	0.0112	0.0093	0.007	0.0044	0	0	0	0	0
11	15.75	0.0302	0.0302	0.0302	0.0302	0.0302	0.0268	0.0223	0.0194	0.0172	0.015	0.0132	0.0114	0.0095	0.0076	0.0055	0.0023	0	0	0	0
12	17.25	0.0304	0.0304	0.0304	0.0304	0.0304	0.0245	0.0214	0.0189	0.0168	0.0149	0.0131	0.0113	0.0097	0.008	0.0061	0.0038	0	0	0	0
13	18.75	0.0306	0.0306	0.0306	0.0306	0.0272	0.0232	0.0204	0.0183	0.0164	0.0147	0.013	0.0114	0.0099	0.0083	0.0067	0.0047	0.0021	0	0	0
14	20.25	0.0308	0.0308	0.0308	0.0308	0.0251	0.0221	0.0199	0.0179	0.0161	0.0145	0.0129	0.0114	0.0099	0.0085	0.007	0.0054	0.0034	0	0	0
15	21.75	0.031	0.031	0.031	0.0278	0.0238	0.0213	0.0193	0.0175	0.0159	0.0142	0.0129	0.0115	0.01	0.0087	0.0073	0.0059	0.0043	0.0019	0	0
16	23.25	0.0313	0.0313	0.0313	0.0259	0.0229	0.0208	0.0189	0.0171	0.0155	0.0142	0.0128	0.0114	0.0102	0.0089	0.0075	0.0062	0.0048	0.0031	0	0
17	24.75	0.0315	0.0315	0.0284	0.0248	0.0222	0.0203	0.0186	0.0169	0.0155	0.0139	0.0127	0.0115	0.0101	0.009	0.0077	0.0065	0.0053	0.0037	0.0017	0
18	26.25	0.0318	0.0318	0.0267	0.0238	0.0216	0.0197	0.0182	0.0167	0.0153	0.0139	0.0127	0.0114	0.0102	0.009	0.0079	0.0069	0.0056	0.0043	0.0027	0
19	27.75	0.0321	0.0291	0.0254	0.0231	0.0211	0.0193	0.0178	0.0163	0.0151	0.0138	0.0126	0.0114	0.0103	0.0093	0.0081	0.0071	0.0059	0.0047	0.0035	0.0015
20	29.25	0.0324	0.0274	0.0247	0.0224	0.0206	0.019	0.0176	0.0161	0.0148	0.0136	0.0126	0.0115	0.0104	0.0093	0.0082	0.0073	0.0062	0.0051	0.0039	0.0025

(example data)

Solve the MDS duration

Example: **Target distribution is uniform.**

Mo

$$\left[\ P_{xr}\ \right]^{-1}\quad \vec{D}(r)\ \vec{T}(x)$$

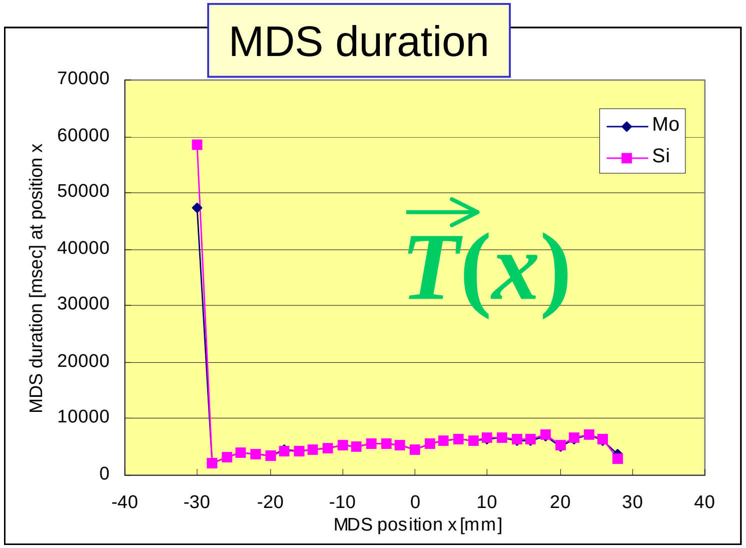
Mo	inverse	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20		d_desire	t1(X)
	r/X	-30	-27	-24	-21	-18	-15	-12	-9	-6	-3	0	3	6	9	12	15	18	21	24	27			
1	0.75	-257.2	486.91	-262	-61.7	502.88	-873.8	951.24	-627.7	-183.2	700.11	-741.2	761.16	-736.8	436.16	1072.4	-1106	-821.9	5619.8	-12324	7469.6		2.625	13.294
2	2.25	348.68	-681.7	114.77	568.12	-761.3	941.54	-1181	973.69	-207.7	-309.1	844.97	-981.5	495.04	532.73	-2225	5871.4	-10868	1671.9	12324	-7470		2.625	5.947
3	3.75	-19.05	63.7	-93.34	131.31	-195.2	53.799	586.03	-1040	1036.3	-657.6	-57.2	787.82	-1157	4251.9	-10447	2360.7	11689	-7292	8E-11	-5E-11		2.625	6.041
4	5.25	-89.41	70.132	511.49	-1059	1039.5	-829.6	514.16	89.861	-1030	1927.9	-2243	4974.5	-10096	1747.7	11600	-7126	-4E-11	8E-11	-2E-10	9E-11		2.625	6.768
5	6.75	208.11	-461.4	85.141	427.93	-204	-29.96	-229.2	804.84	-1213	3952.8	-9088	1223.9	11495	-6968	5E-10	-3E-10	1E-11	-1E-11	2E-11	-1E-11		2.625	7.386
6	8.25	-168.9	434.17	-420.1	329.3	-288.8	707.56	-1840	4883.1	-8916	762.97	11285	-6766	2E-10	-2E-11	-3E-10	4E-11	4E-10	-1E-10	-3E-10	2E-10		2.625	8.334
7	9.75	63.183	-144.6	402.81	-240.4	-1122	4314.7	-8155	748.46	10513	-6377	8E-11	6E-11	-3E-10	8E-11	2E-10	-9E-14	-3E-10	-7E-12	5E-10	-3E-10		2.625	8.589
8	11.25	-232.8	799.8	-1485	3577.9	-7076	898.59	9353.3	-5832	-4E-10	3E-10	-1E-10	-8E-11	4E-10	-2E-10	-3E-10	2E-10	-7E-11	8E-12	9E-11	-5E-11	x	2.625	9.860
9	12.75	-500	2277.4	-5331	635.21	8104.8	-5183	-2E-10	-2E-10	6E-10	-2E-10	-6E-10	3E-10	6E-11	1E-11	-1E-10	9E-11	-1E-11	-5E-12	4E-11	-2E-11		2.625	9.579
10	14.25	-2157	-7.658	6477.2	-4309	-3E-11	7E-11	-1E-10	3E-10	-4E-10	6E-11	5E-10	-3E-10	-1E-11	-2E-11	8E-11	-4E-11	-2E-11	3E-11	-5E-11	3E-11		2.625	9.711
11	15.75	5711	-5708	1E-10	-9E-11	-5E-11	1E-10	-2E-10	4E-11	1E-10	-1E-10	8E-11	3E-11	-2E-10	4E-11	2E-10	-1E-10	-1E-10	1E-10	-6E-11	4E-11		2.625	8.448
12	17.25	-2182	-360.6	7256.8	-4710	-4E-11	8E-11	-2E-10	3E-10	-5E-10	7E-11	5E-10	-3E-10	-2E-11	-2E-11	1E-10	-5E-11	-4E-11	4E-11	-6E-11	3E-11		2.625	10.354
13	18.75	-553.2	2536.9	-5856	186.34	9803.8	-6114	-2E-10	-2E-10	7E-10	-2E-10	-6E-10	4E-10	6E-11	2E-11	-1E-10	1E-10	-2E-11	-1E-12	4E-11	-3E-11		2.625	10.990
14	20.25	-295.6	1003.4	-1835	4364.9	-8431	404.12	12219	-7426	-5E-10	3E-10	-2E-10	-1E-10	6E-10	-2E-10	-3E-10	2E-10	-1E-10	2E-11	1E-10	-6E-11		2.625	12.235
15	21.75	75.926	-172.7	523.39	-320.5	-1498	5708.9	-10493	123.74	14819	-8763	1E-10	7E-11	-4E-10	1E-10	3E-10	2E-11	-5E-10	3E-13	7E-10	-4E-10		2.625	11.518
16	23.25	-262.1	670.4	-617.9	446.95	-443.4	1098.8	-2674	6924.9	-12331	59.491	17162	-10030	3E-10	-4E-11	-5E-10	9E-11	5E-10	-1E-10	-4E-10	2E-10		2.625	12.059
17	24.75	308.1	-677	89.741	702.96	-376.4	39.879	-461.3	1330.6	-1831	5912.1	-13502	755.26	18851	-11137	8E-10	-5E-10	6E-12	-3E-11	6E-11	-4E-11		2.625	11.530
18	26.25	-159.9	137.68	856.02	-1791	1738.3	-1358	802.87	213.92	-1724	3161.3	-3670	8166.1	-16285	1675	20521	-12279	-8E-11	1E-10	-2E-10	1E-10		2.625	11.373
19	27.75	-53.57	142.9	-116	108.82	-251.4	41.911	1074.2	-1855	1838	-1175	-99.4	1395.9	-1978	7435.1	-18162	2892.1	22308	-13543	2E-10	-1E-10		2.625	10.888
20	29.25	690.96	-1349	228.18	1134.7	-1581	1974.8	-2396	1924.6	-342.7	-697.5	1676.3	-1906	988.81	1022.3	-4440	11465	-20441	1664.1	25340	-14952		2.625	11.682
																							sum=	196.5851

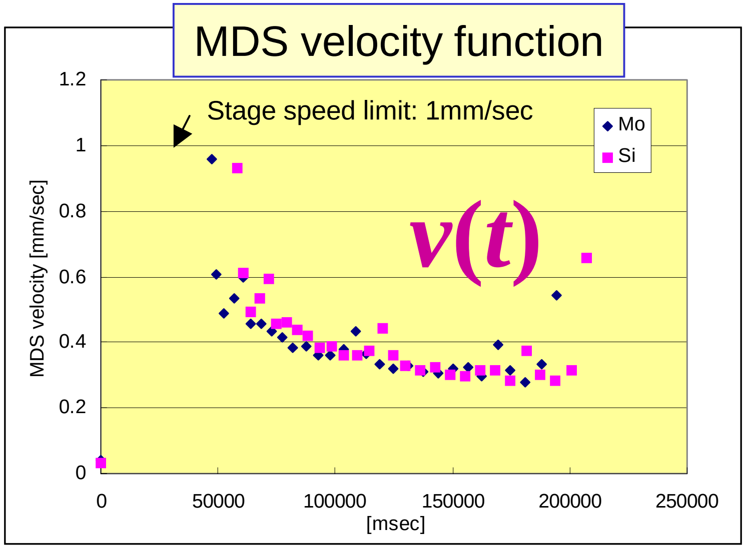
(example data)

Target thickness of Mo is 2.625nm (uniform).
Make product of the **inversed matrix** and the **vectorized distribution**.
Obtain the **vectorized durations** that the MDS should stay at each position. (Total time of MDS scanning is also obtained.)

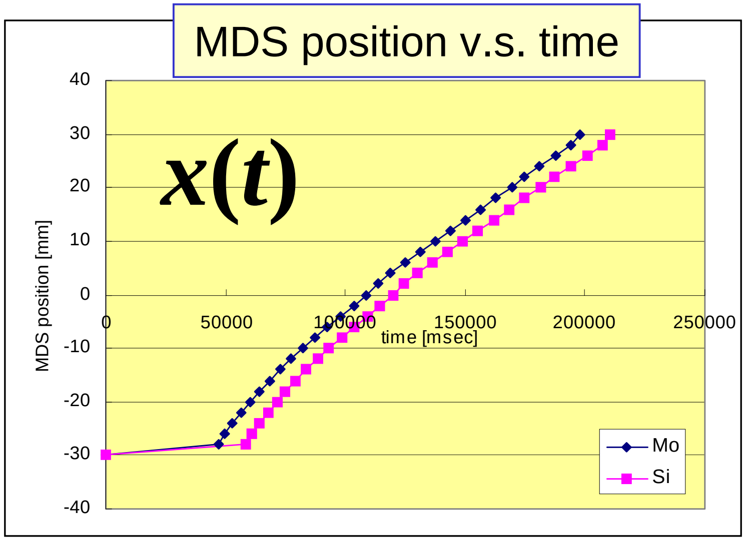
Solution

MDS duration, velocity function,and actual stage positioning


MDS duration


MDS velocity function

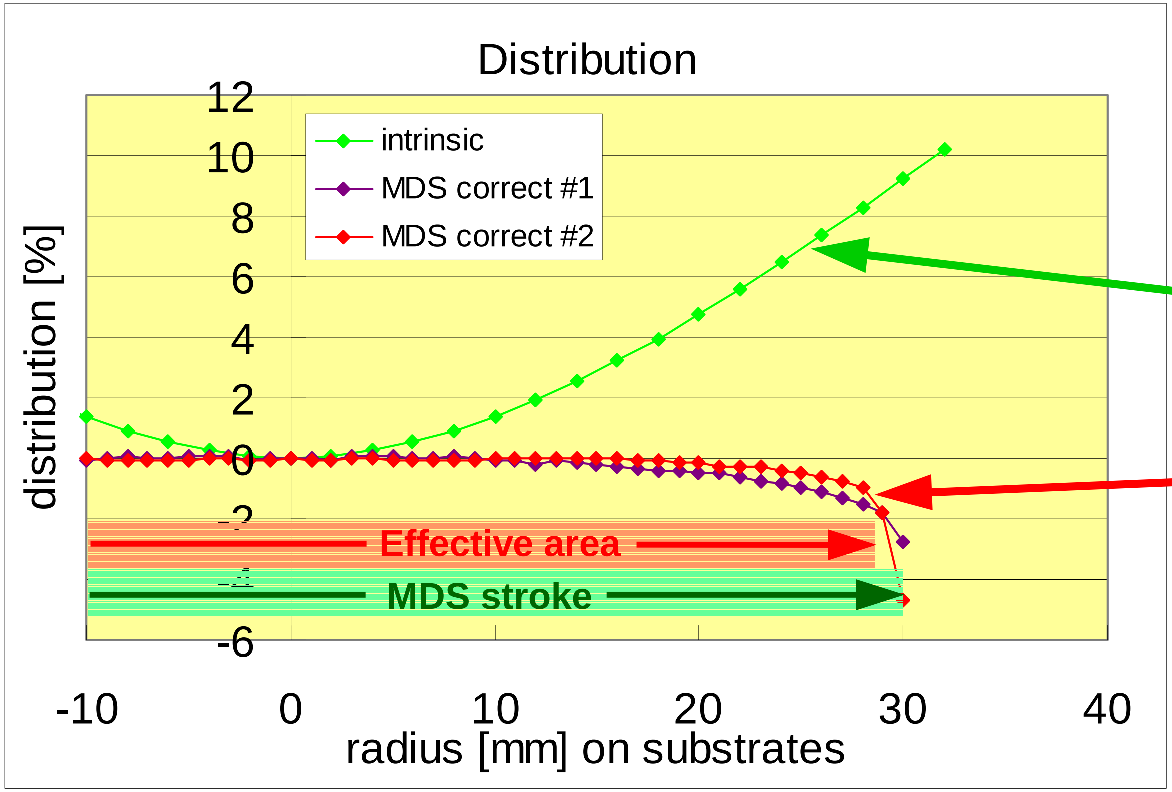
Distribution : uniform (target)
Thickness : Mo 2.625nm
Si 4.875nm


MDS position v.s. time

Max stage speed : <1mm/sec
Correction area : –30mm (full open)
~ +30mm (full closed)

Results of correction

Correction of distribution of Mo/Si multilayers (First attempt)



MDS stroke : 60mm
Effective area:~58mm

No mask:
approx. 10% p-v

With MDS correction:
#1 < 1.5% p-v
#2 < 0.96% p-v
(<0.2% p-v in 40mm)

We applied the **MDS system** to Mo/Si deposition and obtained thickness uniformity correction less than 1% over ~60mm-diameter area. We can apply this system for not only a uniform target but also any distribution required.

Summary

* We constructed an **experimental thickness distribution control and correction system** with a **moving deposition shutter (MDS)** to a rotary magnet cathode (RMC) sputtering system.

* We applied this MDS system to the deposition of **Mo/Si multilayers**, and obtained thickness uniformity correction **less than 1%** over approx. 60mm-diameter area at the first attempt from the intrinsic distribution greater than 10%.

We confirmed the fundamental proof of distribution correction with the MDS system and the inversed matrix method.

By refinement of calculation for correction, distribution error will be reduced.

* We can apply this system for not only a uniform target but also any distribution required.

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