

The Estimation of Cost of Ownership of EUV and ArF-Immersion Exposure Systems

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1. Background

Device Sub-Working Group of EUVA estimated the Cost of Ownership of EUV and ArF-Immersion exposure systems from 65nmHP to 32nmHP nodes. I-SEMATECH has estimated that at the 45nmHP node (eq. 32nm device node), the lithography cost might be over 50% of the wafer production cost on the level of production of 2k wafers per one mask. This means mask cost and exposure related cost might be equivalent.

Our work is focused on comparing the Cost of Ownership of EUV Lithography and ArF-Immersion, recently put into mass production market. Estimated ArF-Immersion System includes Double Patterning System. Based on the mask cost estimation, herein attached, the costs of exposure were evaluated on each generation.

At 45nmHP node (eq. 32nm device node) ArF-Immersion should adopt strong resolution technology, trimming and/or double patterning, if it would use water as immersion liquid and NA might be 1.3 at the maximum. This inevitably leads ArF-Immersion to introduce complicated OPC mask or two masks & exposure process, then it would cause the steep rise of exposure cost for critical layer. In such situation, EUV lithography would be highly competent tool for 45mHP.

2. Calculation Method of exposure system

The following is a formula for cost estimation.

$$C = CE / (T \cdot U \cdot N \cdot Y) + CM + CR$$

Where,

C : Cost of exposure for one wafer at once,

CE: Depreciation and operating cost of lithography related tools per year,

T : Throughput of exposure system (wafer/hour),

U : Actual operating rate of exposure system (excluding time for calibration, setup of exposure condition, and pilot wafer exposure)

N : Total annual operating hours of exposure system

Y : Yield of exposure process

CM: Mask cost of exposure for one wafer at once

CR: Resist process cost of exposure for one wafer at once

Then $CE=CT + CO + CS$

Where

CT: Annual depreciation cost of exposure system

CO: Annual operating cost of lithography related tools (power usage, expendables, maintenance cost, and labor cost of operator)

CS: Annual depreciation cost of building and clean room per m^2 , multiplied by footprint of exposure system

3. Exposure Method

The following lithography methods are considered, with 90nmHP ArF(NA=0.93, $k_1=0.43$) as a starting reference;

- (1) **90nmHP**: ArF Dry, NA=0.93, $k_1=0.43$ with HT mask and exposure at once
- (2) **80nmHP**: ArF-I, NA=1.0, $k_1=0.41$ with HT mask and exposure at once
- (3) **65nmHP**: ArF-I, NA=1.3, $k_1=0.43$ with HT mask and exposure at once
- (4) -1 **45nmHP**: ArF-I, NA=1.3, $k_1=0.30$ with RET mask & trimmed mask and exposure at twice
- (4) -2 **45nmHP**: ArF-I, NA=1.3, $k_1=0.61$, double pitch with HT mask and exposure at twice (Double Patterning)
- (4) -3 **45nmHP**: ArF-I, NA=1.65, $k_1=0.38$ with HT mask and exposure at once
- (4) -4 **45nmHP**: EUVL NA=0.25, $k_1=0.83$ with reflective mask and exposure at once
- (5) -1 **32nmHP**: ArF-I, NA=1.3, $k_1=0.43$, double pitch with HT mask and exposure at twice (Double Patterning)
- (5) -2 **32nmHP**: ArF-I, NA=1.65, $k_1=0.54$, double pitch with HT mask and exposure at twice (Double Patterning)
- (5) -3 **32nmHP**: EUVL, NA=0.25, $k_1=0.59$ with reflective mask and exposure at once
- (6) Throughputs were varied depending on Maskless Delineation.

Table 1 shows major parameters of each exposure system/process,

Table 2 shows five year straight-line depreciation costs of exposure system and resist application/development tool, and operating costs,

Table 3 shows mask cost and expendables relating resist process.

4. Results of CoO estimation

(a) 100k wafers per one mask (Table 4)

The more volume of production, the less the cost of mask affects the CoO. The tool cost and throughput would give major affect to the CoO in this case.

Promising exposure systems in view of the cost are;

- 90/80nmHP: ArF Dry: JPY960 or ArF-I (NA=1.0): JPY1,400
- 65nmHP: ArF-I (NA=1.3): JPY1,630
- 45nmHP: EUVL: JPY2,470 or ArF-I (NA=1.65): JPY2,880
- 32nmHP: EUVL: JPY2,940 < ArF-I (NA=1.3) with DP: JPY3,670 < ArF-I (NA=1.65) with DP: JPY5,910

The cost increases 1.5 to 1.7 times higher than previous generation from 90nm, 80nm to 65nm, however at 45nm the cost of ArF-I (NA=1.3) is soaring up with the use of complex OPC. To alleviate the substantial cost-rise, ArF-I (NA=1.65), which is capable to expose area of 25mmX33mm, or EUVL with throughput of 100wph should be introduced. But we should consider that both systems have high technical difficulties to produce.

At 45nm node, the cost of ArF-I (NA=1.3) with RET & Trimming, and that with twice exposure with Double Patterning, are the same level. In this evaluation, twice exposure requires severe position accuracy for two divided patterned masks, however we did not consider the effect of the relative position accuracy on the yield of wafer etching.

(b) 10k wafers per one mask (Table 5)

The estimation is almost the same as the case of 100k wafers per one mask. But the cost of process which uses two masks increases drastically.

- 90/80nmHP: ArF Dry: JPY1,340, or ArF-I (NA=1.0): JPY1,780
- 65nmHP: ArF-I (NA=1.3): JPY2,230
- 45nmHP: ArF-I (NA=1.65): JPY3,560, EUVL: JPY3,500 < ArF-I (NA=1.3) with strong RET & trimming: JPY5,770 < ArF-I (NA=1.3) with Double Patterning: JPY6,080
- 32nmHP: EUVL: JPY4,400 < ArF-I (NA=1.65) with Double Patterning: JPY7,970, ArF-I (NA=1.3) double Patterning: JPY8,460

(c) 500 wafers per one mask (Table 6)

In this medium volume production case, mask cost is contributing more and more to CoO. Mask cost is consisting major parts of lithography cost with the use of OPC and/or twice exposure.

- 90/80nmHP: ArF Dry: JPY9,320, or ArF-I (NA=1.0): JPY9,760
- 65nmHP: ArF-I (NA=1.3): JPY14,870
- 45nmHP: ArF-I (NA=1.65): JPY17,870 < EUVL: JPY25,350 << ArF-I (NA=1.3) with strong RET & trimming: JPY55,800, or ArF-I (NA=1.3) with Double Patterning:

JPY62,000

- 32nmHP: EUVL: JPY35,400, or ArF-I (NA=1.65) with Double Patterning: JPY51,620
<ArF-I (NA=1.3) with Double Patterning: JPY50,300

* At 32nmHP level, the cost of Maskless Direct Delineation is approaching that of Mask Lithography, if Maskless's throughput would be more than 3wph.

* The reason that ArF-I (NA=1.65) with Double Patterning is most cost effective, is coming from its small exposure area and the improved mask yield.

(d) 100 wafers per one mask (Table 7)

In the small quantity production case, MCC of Maskless Exposure (JPY31,100@5wph) and CP-EBDW (JPY41,600@2wph) would be promising tools.

- 90/80nmHP: ArF Dry: JPY43,200, or ArF-I (NA=1.0): JPY43,700
- 65nmHP: ArF-I (NA=1.3): JPY68,500
- 45nmHP: ArF-I (NA=1.65): JPY77,200, or EUVL: JPY118,000
- 32nmHP: EUVL: JPY166,200

In this production case, Maskless Direct Delineation (>2wph) is also promising at 45nmHP node or beyond.

5. Conclusion (Figures 1- 4)

EUVL and ArF-Immersion were considered as a candidate for 45nmHP and 32nmHP lithography tool.

- At 90 to 65nmHP node, ArF Dry and ArF-immersion (NA=1.0) are considered as affordable tools because their exposure methods have almost completed and its cost increase lies on historical trends, in particular for critical layers.
- At 45nmHP node, the most cost effective tool seems to be ArF-Immersion (NA=1.65), because $k_1=0.38$ is nearly equal to the existing tools and OPC is relatively easy to make. But we should take note that ArF-Immersion (NA=1.65) tool has high technical difficulties and its production is very pessimistic at present, because high reflectivity materials, including lens, immersion liquid, and resist, are requisite but we have no solutions.
- At 45nmHP, ArF-Immersion (NA=1.3) is rather easy to produce, since immersion liquid is water, and the current lens/resist materials are used as well. But $k_1=0.30$ is near the minimum limit, and it requires RET and complex OPC.
- EUVL at 45nmHP has several upsides; $k_1>0.8$ has relatively large margin, only week OPC is needed and the cost of mask is low. In view of exposure cost, EUVL is more favorable as the production volume becomes smaller. But it is concerned

that at the time of device production, tool and infrastructure might not become enough level for use.

- At 32nmHP, every ArF type must adopt twice exposure process, unless IC pattern be restricted to specific ones. Twice exposure requires sever accuracy for position and alignment of two masks and tool.
- At 32nmHP or beyond, Maskless exposure might be promising, though the development risk is very high.

Table 1. Fundamental Parameters for various lithography systems

Exposure System	Field Size	Wafer Size	Throughput (ϕ 300 mm)	Tool Cost (million Yen)	Comments
		ϕ	TG		
	(mm)	(mm)	wafers/h		
ArF	25X33	300	100	1,500	90 nm scanner
ArF-I (NA=1.0)	25X33	300	100	2,500	
ArF-I (NA=1.3)	25X33	300	100	30,00	Cost is estimated
ArF-I (NA=1.65)	15X33	300	60	35,00	Cost is estimated (exposure areas is small)
EUVL(45nm)	25X33	300	100	50,00	Cost is estimated
EUVL(32nm)	25X33	300	100	6,000	Cost is estimated
EBDW		300	1	900	Cost is estimated
Low-Acceleration CP-EBDW	1250 (μ m)	300	2	1,200	Converted Throughput of ϕ 300mm
MCC	100 μ m	300	5	25,00	Converted Throughput of ϕ 301mm

Table 2. Cost of Depreciation of Exposure Systems & Resist Coater/Developer, Operating & Maintenance and Floor

Tool Generation/Exposure System		Item	90 nm	80nm	65nm	45nm			32nm			65~45nm			Comments
			ArF	ArF-I (NA=1.0)	ArF-I (NA=1.3)	ArF-I (NA=1.3)	ArF-I (NA=1.65)	EUVL(45) (NA=0.25)	ArF-I (NA=1.3) & DP	ArF-I (NA=1.65) & DP	EUVL(32)(NA=0.25)	EBDW	L-A CP-EBDW	MCC	
Initial Investment for Equipment	Stepper (1set)	(Million Yen)	1500	2500	3,000	3000	3500	5000	3000	3500	6000	900	1200	2500	Cost is estimated for ArF-I and EUVL.. Throughput of EUVL is expected to go up to 100wph. The cost increase for ArF-I DP is excluded.
	Resist Coater/developer	(Million Yen)	250	250	250	250	250	250	250	300	300	250	250	250	
	Sub Total	(Million Yen)	1,750	2,750	3,250	3,250	3,750	5,250	3,250	3,800	6,300	1,150	1,450	2,750	
	Annual Depreciation Cost (CT)	(Million Yen/Year)	350	550	650	650	750	1,050	650	760	1,260	230	290	550	Five Year Fixed Installment
Operating Cost	Power Usage Cost	(Million Yen/Year)	25	25	25	25	25	35	25	25	35	15	15	25	Electric Power, Coolant, Nitrogen, etc.
	Maintenance Cost	(Million Yen/Year)	52.5	82.5	97.5	97.5	112.5	157.5	97.5	114	189	34.5	43.5	82.5	3% of purchased price of each equipment. ArF, F2: optical parts, laser, and gas charge costs are big. The cost of EPL, using step scanner, is twice of EBDW. EUV has possibility of more cost depending on plasma debris mitigation.
	Operating Labor Cost	(Million Yen/Year)	3.3	3.3	5	5	5	5	5	5	5	5	5	5	Number of tool operated by one person: 3 tools for ArF, F2, 2 tools for EBDW, EPL, EUV. Labor cost is 10MYen/year.man.
	Operating/Maintenance Cost (CO)	(Million Yen/Year)	80.8	110.8	127.5	127.5	142.5	197.5	127.5	144	229	54.5	63.5	112.5	
Floor	Foot Print	(m2)	20	20	20	20	20	40	20	20	40	20	20	20	
	Floor Cost (CS)	(Million Yen/Year)	2	2	2	2	2	5	2	2	5	2	2	2	Floor cost is 120,000Yen/m2*year
CE = CT+Co+Cs		(Million Yen)	433	663	780	780	895	1,252	780	906	1,494	287	356	665	

Table 3. Mask and Resist Cost

Device-Generation/Exposure System Item		90 nm	80nm	65nm	45nm				32nm						Comments
		ArF	ArF-I (NA=1.0)	ArF-I (NA=1.3)	ArF-I (NA=1.3)	ArF-I (NA=1.3) & DP	ArF-I (NA=1.65)	EUVL(45)	ArF-I (NA=1.3) &DP	ArF-I (NA=1.65) &DP	EUVL(32)	EBDW	Low-Acc. CP-EBDW	MCC	
Mask Cost	(10,000Yen per Mask)	420	420	665	2633	2949	735	1150	5323	2297	1624	0	0	0	Cost caused by twice etching at Double-Patterning is not considered. Two masks are both used for critical layers. Mask Costs for EBDW and MCC are negligible.
Resist Cost	(10,000Yen per gallon)	25	35	35	35	35	35	25	35	35	25	25	25	25	Paint of resist per wafer is 1.5 ml. KrF is actual value and others are estimated value at production.
Resist Cost per Wafer	(Yen)	99	139	139	139	277	139	99	277	277	99	99	99	99	
Developer Cost	(Yen/gallon)	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	5,000	Developer consumption per wafer is 50 ml.
Developer Cost per Wafer	(Yen)	66	66	66	66	132	66	66	132	132	66	66	66	66	
Total of Resist Cost and Developer Cost	(Yen)	165	205	205	205	409	205	165	410	410	165	165	165	165	

Table 4. CoO estimation (100,000 wafers per mask)

Device Generation		90 nm	80nm	65nm	45nm				32nm		
Exposure System		ArF	ArF-I (NA=1.0)	ArF-I (NA=1.3)	ArF-I (NA=1.3)	ArF-I (NA=1.3) &DP	ArF-I (NA=1.65)	EUVL(45)	ArF-I (NA=1.3) &DP	ArF-I (NA=1.65) &DP	EUVL(32)
Depreciation Caost of Equipment and Operation/Maintenance Cost	(Million Yen)	433	663	780	780	780	895	1252	780	905	1494
Throughput	(Wafer/Hour)	100	100	100	50	50	60	100	50	30	100
Actual Operating Hours of System	(%)	80	80	80	80	80	80	80	80	80	80
Annual Operating Hours	(h)	8424	8424	8424	8424	8424	8424	8424	8424	8424	8424
Yield of Wafer in Exposure Process	(%)	85	85	85	85	85	85	85	85	85	85
Depreciation Cost and Operation/Maintenance Cost per Wafer per Exposure	(Yen)	756	1157	1362	2723	2723	2604	2186	2723	5266	2608
Mask Cost per Wafer per Exposure	(Yen)	42	42	66.5	263.3	294.9	73.5	115	532.3	229.7	162.4
Resist and developer Cost per Wafer per Exposure	(Yen)	165	205	205	410	410	205	165	410	410	165
Exposure Cost per Wafer per Exposure	(Yen)	963	1404	1633	3397	3428	2883	2466	3666	5906	2935
Cost Ratio to ArF (90 nmHP node)		1.0	1.5	1.7	3.5	8.6	3.0	2.6	3.8	6.1	3.0

Table 5. CoO Estimation (10,000 Wafers/Mask)

Device Generation		90 nm	80nm	65nm	45nm				32nm			65~45nm		
Exposure System		ArF	ArF-I (NA=1.0)	ArF-I (NA=1.3)	ArF-I (NA=1.3)	ArF-I (NA=1.3) &DP	ArF-I (NA=1.65)	EUVL(45)	ArF-I (NA=1.3) &DP	ArF-I (NA=1.65) & DP	EUVL(32)	EBDW	Low-Acc. CP- EBDW	MCC
Depreciation Caost of Equipment and Operation/Maintenance Cost	(Million Yen)	433	663	780	780	780	895	1252	780	905	1494	287	356	665
Throughput	(Wafer/ Hour)	100	100	100	50	50	60	100	50	30	100	1	2	5
Actual Operating Hours of System	(%)	80	80	80	80	80	80	80	80	80	80	80	80	80
Annual Operating Hours	(h)	8424	8424	8424	8424	8424	8424	8424	8424	8424	8424	8424	8424	8424
Yield of Wafer in Exposure Process	(%)	85	85	85	85	85	85	85	85	85	85	85	85	85
Depreciation Cost and Operation/Maintenance Cost per Wafer per Exposure	(Yen)	756	1157	1362	2723	2723	2604	2186	2723	5266	2608	50102	31074	23218
Mask Cost per Wafer per Exposure	(Yen)	420	420	665	2633	2949	753	1150	5323	2297	1624	0	0	0
Resist and developer Cost per Wafer per Exposure	(Yen)	165	205	205	410	410	205	165	410	410	165	165	165	165
Exposure Cost per Wafer per Exposure	(Yen)	1341	1782	2232	5766	6082	3562	3501	8456	7973	4397	50267	31239	23383
Cost Ratio to ArF (90 nmHP node)		1.0	1.3	1.7	4.3	4.5	2.7	2.6	6.3	5.9	3.3	37.5	23.3	17.4

Table 6. CoO Estimation (500 Wafers/Mask)

Device Generation		90 nm	80nm	65nm	45nm				32nm			65~45nm		
Exposure System		ArF	ArF-I (NA=1.0)	ArF-I (NA=1.3)	ArF-I (NA=1.3)	ArF-I (NA=1.3) & DP	ArF-I (NA=1.65)	EUVL(45)	ArF-I (NA=1.3)&DP	ArF-I (NA=1.65) &DP	EUVL(32)	EBDW	Low-Acc. CP-EBDW	MCC
Depreciation Caost of Equipment and Operation/Maintenance Cost	(Million Yen)	433	663	780	780	780	895	1252	780	906	1496	287	356	665
Throughput	(Wafer/ Hour)	100	100	100	50	50	60	100	50	30	100	1	2	5
Actual Operating Hours of System	(%)	80	80	80	80	80	80	80	80	80	80	80	80	80
Annual Operating Hours	(h)	8424	8424	8424	8424	8424	8424	8424	8424	8424	8424	8424	8424	8424
Yield of Wafer in Exposure Process	(%)	85	85	85	85	85	85	85	85	85	85	85	85	65
Depreciation Cost and Operation/Maintenance Cost per Wafer per Exposure	(Yen)	756	1157	1362	2723	2723	2604	2186	2723	5272	2612	50102	31074	30362
Mask Cost per Wafer per Exposure	(Yen)	8400	8400	13300	52660	58980	15060	23000	106460	45940	32480	0	0	0
Resist and developer Cost per Wafer per Exposure	(Yen)	165	205	205	410	410	205	165	410	410	165	165	165	165
Exposure Cost per Wafer per Exposure	(Yen)	9321	9762	14867	55793	62113	17869	25351	109593	51622	35257	50267	31239	30527
Ratio of Mask Cost to Total Cost		90	86	89	94	95	84	91	97	89	92	0	0	0
Cost Ratio to ArF (90 nmHP node)		1.0	1.0	1.6	6.0	6.7	1.9	2.7	11.8	5.5	3.8	5.4	3.4	3.3

Table 7. CoO Estimation (100 Wafers/Mask)

Device Generation		90 nm	80nm	65nm	45nm				32nm			65~45nm		
Exposure System		ArF	ArF-I (NA=1.0)	ArF-I (NA=1.3)	ArF-I (NA=1.3)	ArF-I (NA=1.3) & DP	ArF-I (NA=1.65)	EUVL(45)	ArF-I (NA=1.3) &DP	ArF-I (NA=1.65) & DP	EUVL(32)	EBDW	Low-Acc. CP-EBDW	MCC
Depreciation Caost of Equipment and Operation/Maintenance Cost	(Million Yen)	433	663	780	780	780	895	1252	780	905	1264	287	356	665
Throughput	(Wafer/ Hour)	100	100	100	50	50	60	100	50	30	80	1	2	5
Actual Operating Hours of System	(%)	60	60	60	60	60	60	60	60	60	60	60	60	60
Annual Operating Hours	(h)	8424	8424	8424	8424	8424	8424	8424	8424	8424	8424	8424	8424	8424
Yield of Wafer in Exposure Process	(%)	85	85	85	85	85	85	85	85	85	85	85	85	85
Depreciation Cost and Operation/Maintenance Cost per Wafer per Exposure	(Yen)	1008	1543	1816	3631	3631	3472	2914	3631	7022	3678	66803	41432	30957
Mask Cost per Wafer per Exposure	(Yen)	42000	42000	66500	263300	294900	73500	115000	532320	229700	162400	0	0	0
Resist and developer Cost per Wafer per Exposure	(Yen)	165	205	205	410	410	205	165	410	410	165	165	165	165
Exposure Cost per Wafer per Exposure	(Yen)	43173	43748	68521	267341	298941	77177	118079	536361	237132	166243	66968	41597	31122
Ratio of Mask Cost to Total Cost		97	96	97	98	99	95	97	99	97	98	0	0	0
Cost Ratio to ArF (90 nmHP node)		1.0	1.0	1.6	6.2	6.9	1.8	2.7	12.4	5.5	3.9	1.6	1.0	0.7

Figure 1. Exposure Cost (100,000 Wafers/Mask)

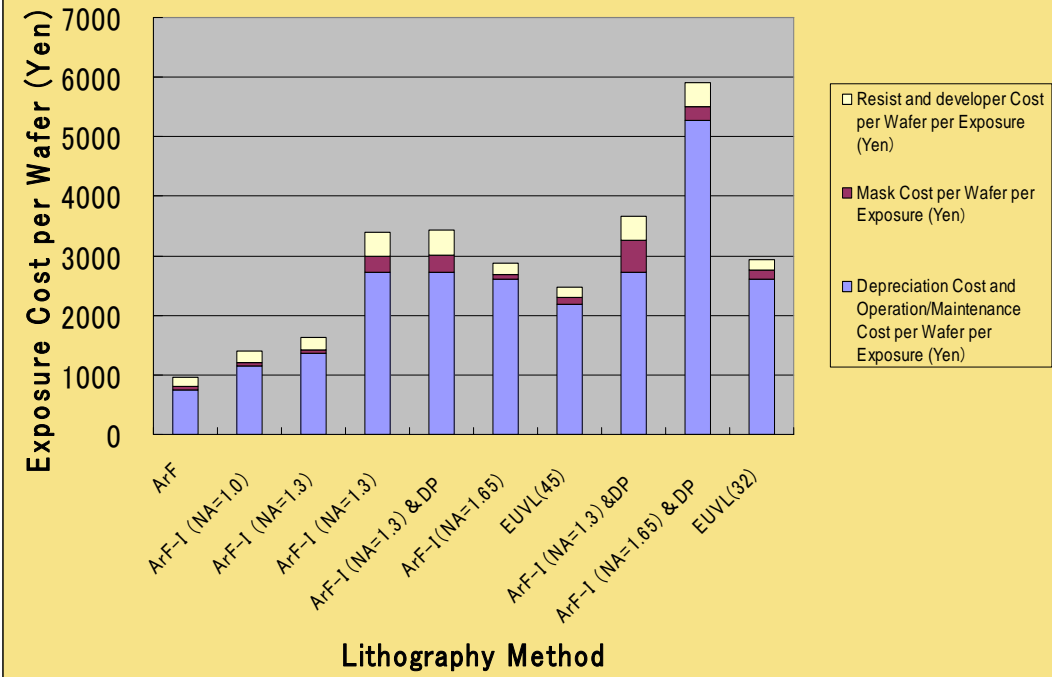


Figure 2. Exposure Cost (10,000 Wafers/Mask)

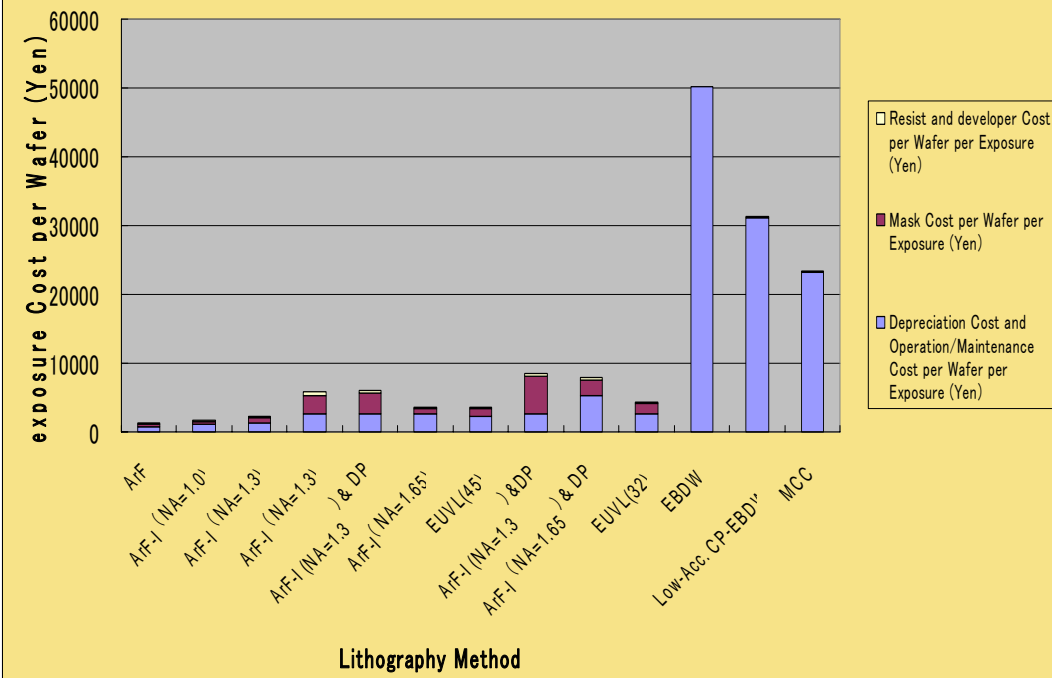


Figure 3. Exposure Cost (500 Wafers/Mask)

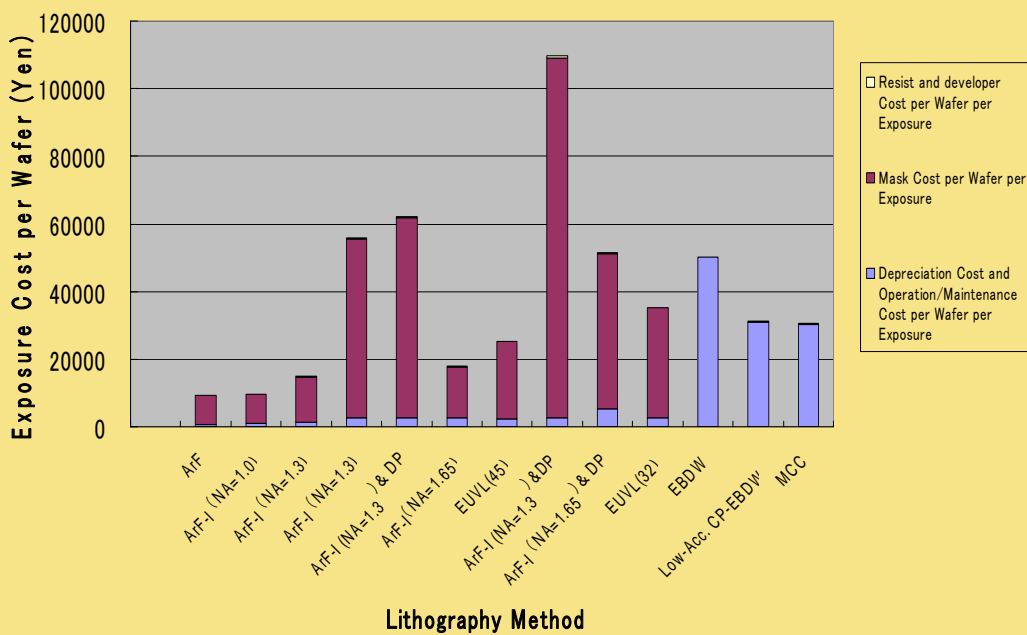


Figure 4. Exposure Cost (100 Wafers/Mask)

